High School Teachers 2014

http://indico.cern.ch/event/318730/other-view?view=standard

• Particle Detectors •

Mar Capeans

CERN, July 10th 2014

• Particle Detectors•

OUTLINE

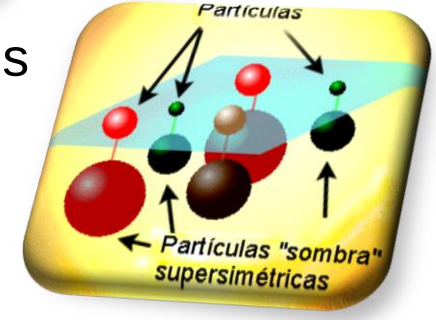
1. Historical Overview
2. Particle Detector Challenges at LHC
3. Interactions of Particles with Matter
4. Detector Technologies
5. How HEP Experiments Work

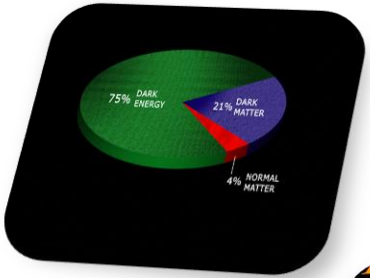
45+10 min
10 min break
45+10 min

Challenges

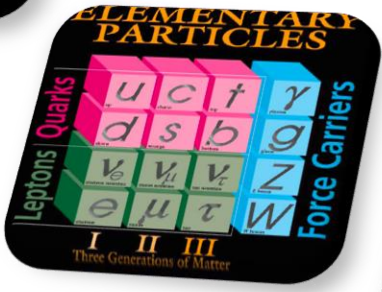
- Mass of particles: Higgs Boson(

- Matter, Dark Matter: Super symmetric particles

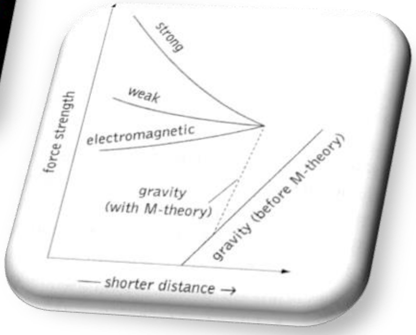




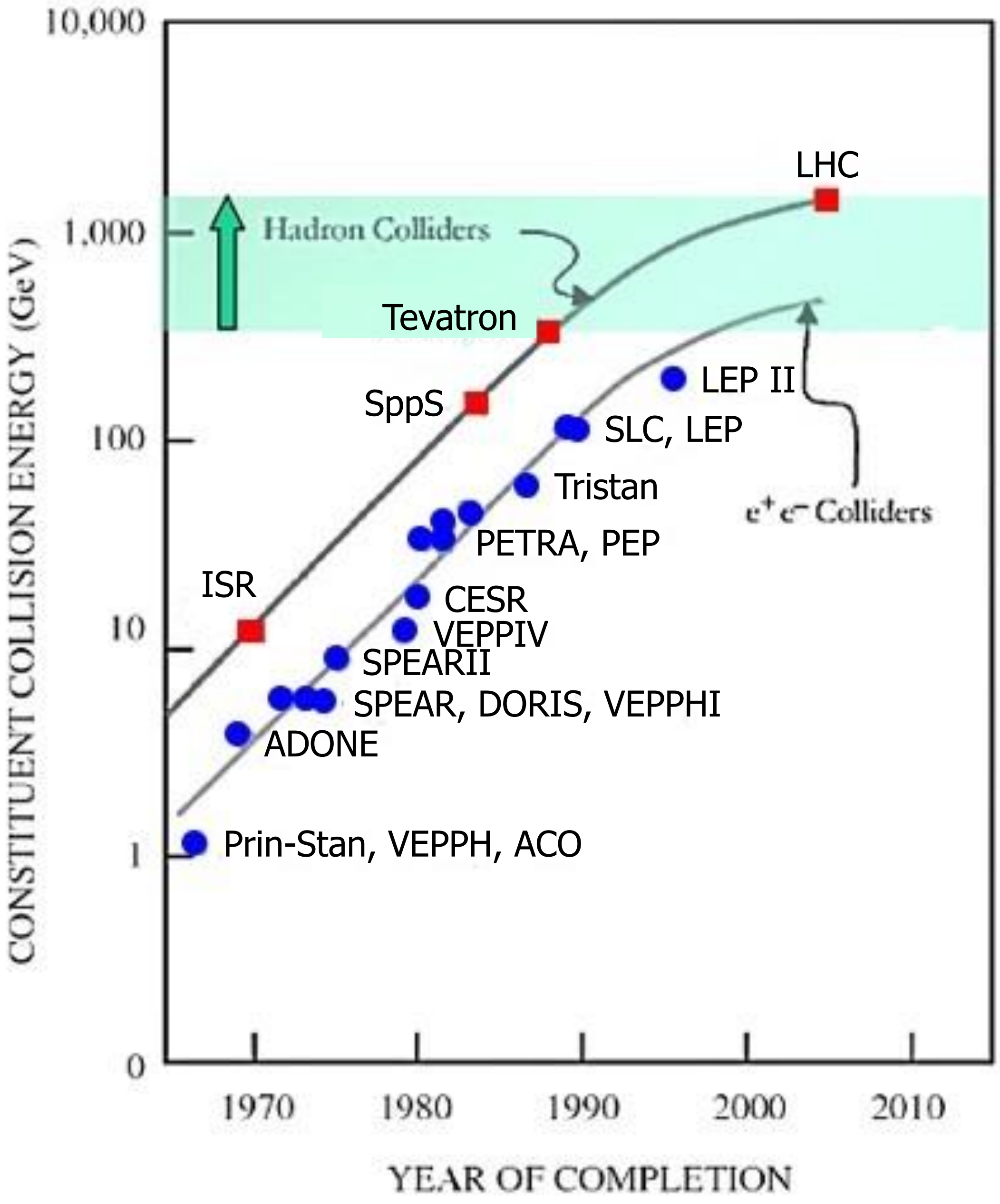
- Matter VS Antimatter
- Fundamental Particles



- New forces, extra dimensions…



Slide: M.Nessi, CERN



- Today HEP main priority is to investigate the new energy domain opened by the LHC (Large Hadron Collider): 7+7 TeV CM energy
- To arrive there the overall HEP community has invested, as never before, in a single facility (here at CERN), the LHC:

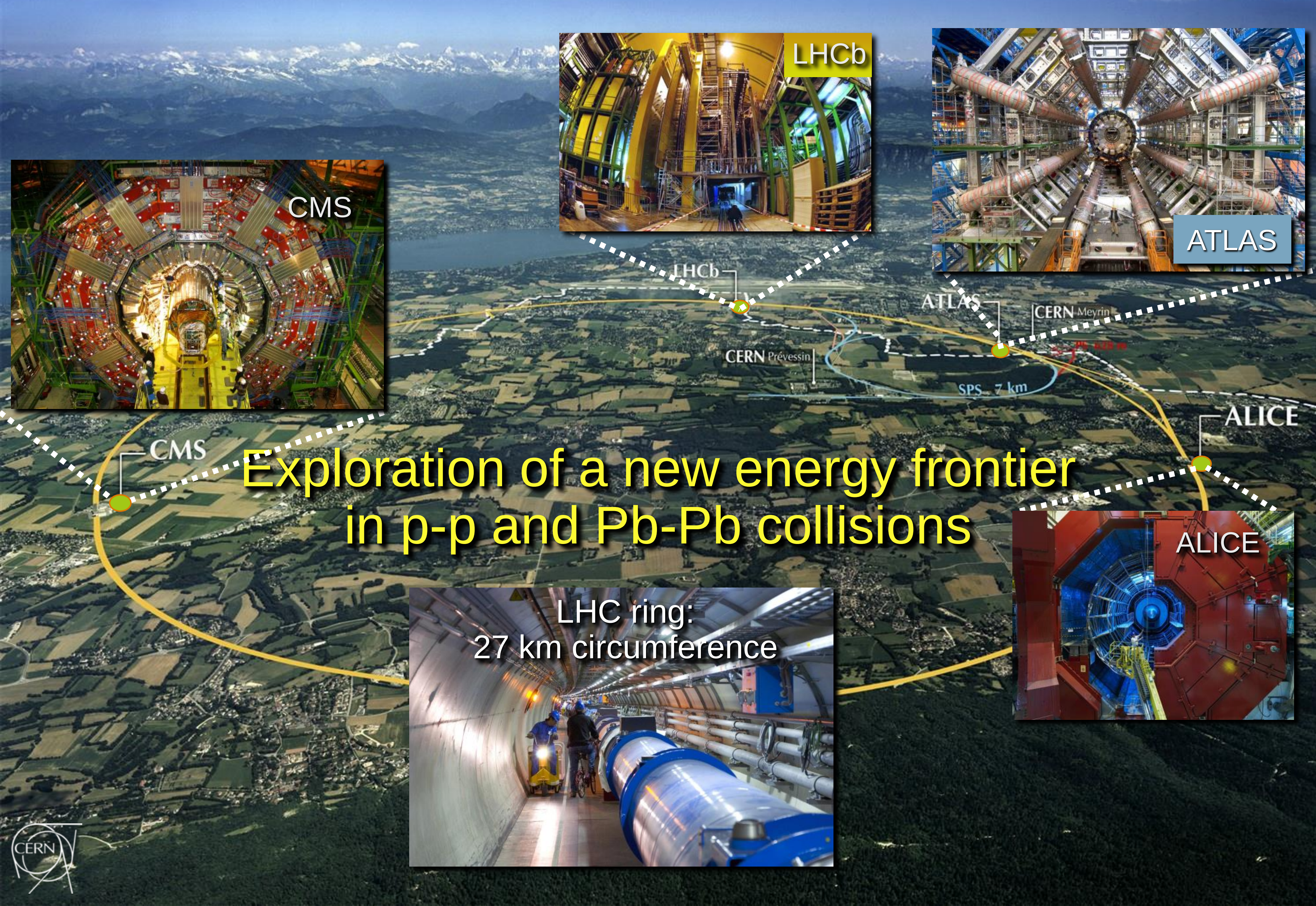
Accelerator

<u>Detectors</u>

Trigger, DAQ

Data Analysis

New Era in Fundamental Science



Exploration of a new energy frontier in p-p and Pb-Pb collisions

LHC ring:
27 km circumference

History

Slide: W.Riegler, CERN

History of Particle Physics

1895: **X-rays**, W.C. Röntgen
1896: **Radioactivity**, H. Becquerel
1899**: Electron**, J.J. Thomson
1911: **Atomic Nucleus**, E. Rutherford
1919: **Atomic Transmutation**, E. Rutherford
1920: **Isotopes**, E.W. Aston
1920-1930: **Quantum Mechanics**, Heisenberg, Schrödinger, Dirac
1932: **Neutron**, J. Chadwick
1932**: Positron**, C.D. Anderson
1937: **Mesons**, C.D. Anderson
1947: **Muon**, Pion, C. Powell
1947: **Kaon**, Rochester
1950: **QED**, Feynman, Schwinger, Tomonaga
1955: **Antiproton**, E. Segre
1956: **Neutrino**, Rheines

Etc. etc. etc.

History of instrumentation

1906: **Geiger Counter**, H. Geiger, E. Rutherford
1910: **Cloud Chamber**, C.T.R. Wilson
1912: **Tip Counter**, H. Geiger

1928: **Geiger-Müller Counter**, W. Müller
1929: **Coincidence Method**, W. Bothe
1930: **Emulsion**, M. Blau

1940-1950: **Scintillator, Photomultiplier**

1952: **Bubble Chamber**, D. Glaser

1962: **Spark Chamber**

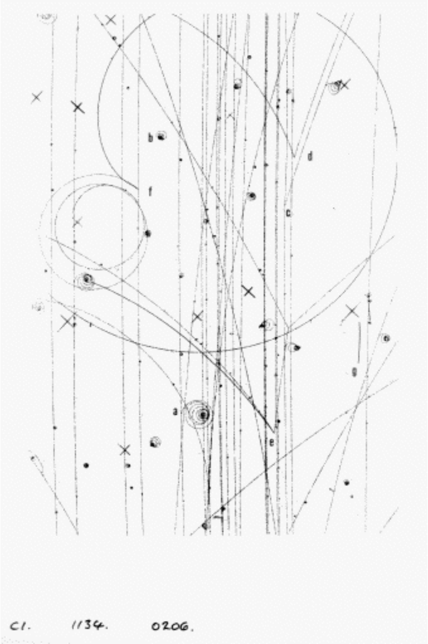
1968: **MultiWire Proportional Chamber**, C. Charpak

Etc. etc. etc.

• History•

Slide: W.Riegler, CERN

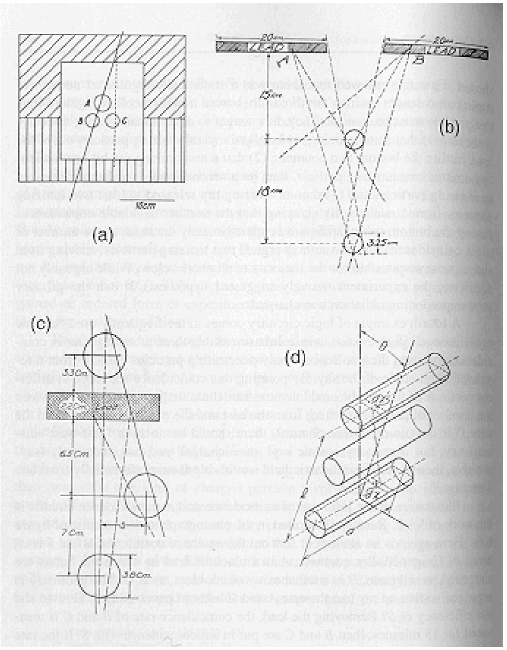
Image Detectors



Bubble chamber photograph

Of the same family:
Emulsion & Bubble Chambers

Logic (electronics) Detectors

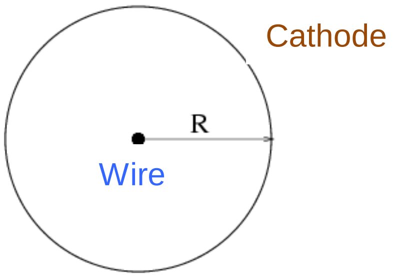


Early coincidence counting experiment

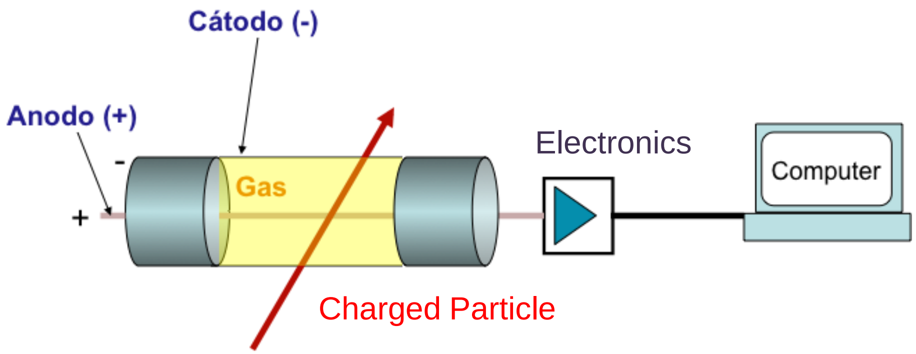
Of the same family:
Scintillator, Geiger counter, Tip counter, Spark counter

High Density Electronics

Tube, Geiger- Müller, 1928

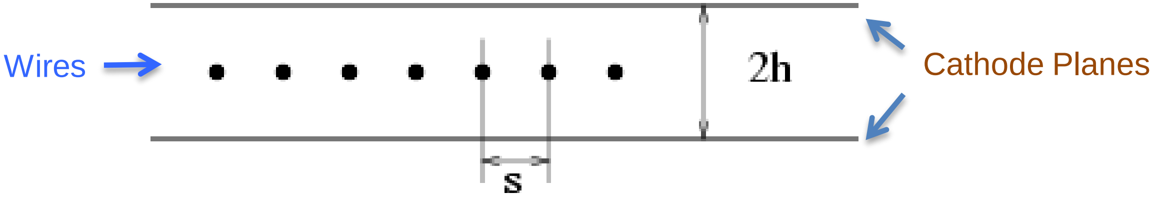


SWPC



G. Charpak (1992 Nobel), **Multi Wire Proportional Chamber (MWPC) 1968**

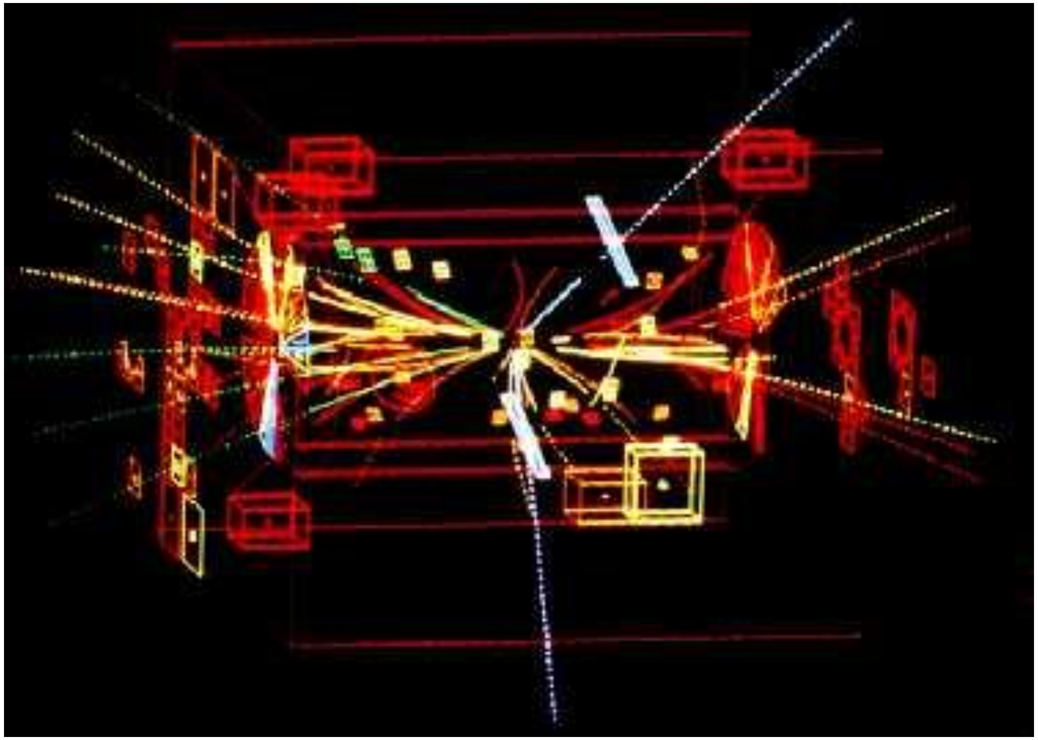
- Readout of individual wires and proportional mode working point
- First electronic device allowing high statistics experiments !!



• History•

Slide: W.Riegler, CER

Both traditions combine into the ‘Electronics Image’ during the 1970ies

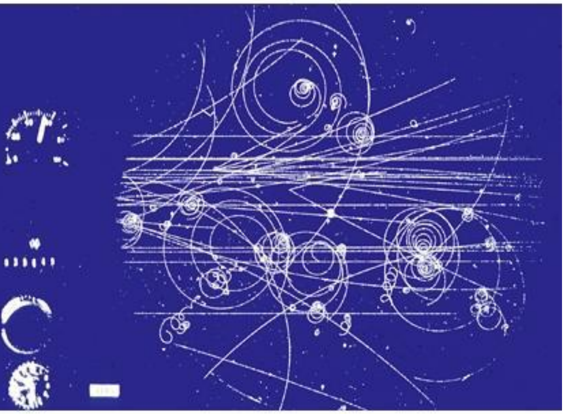


Z-Event at UA1 / CERN

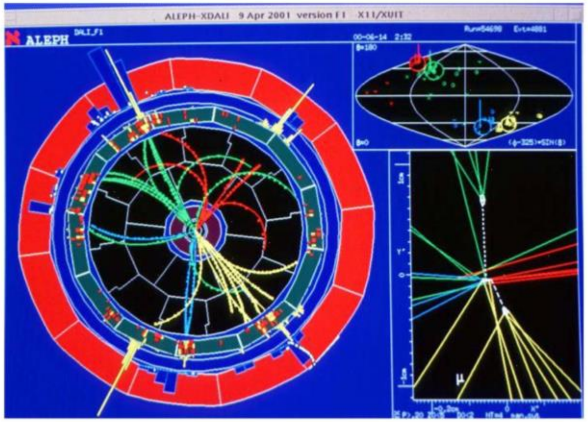
Computer reconstruction of tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.

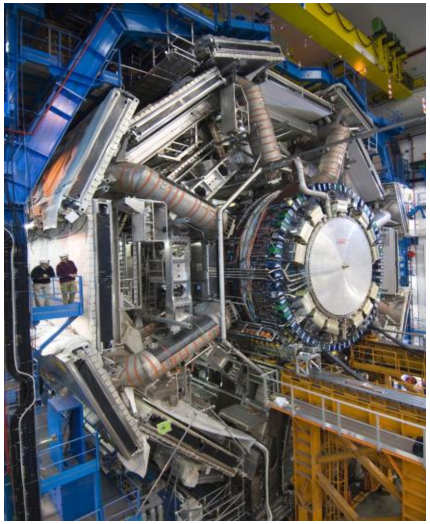
Imaging Events

50’s – 70’s

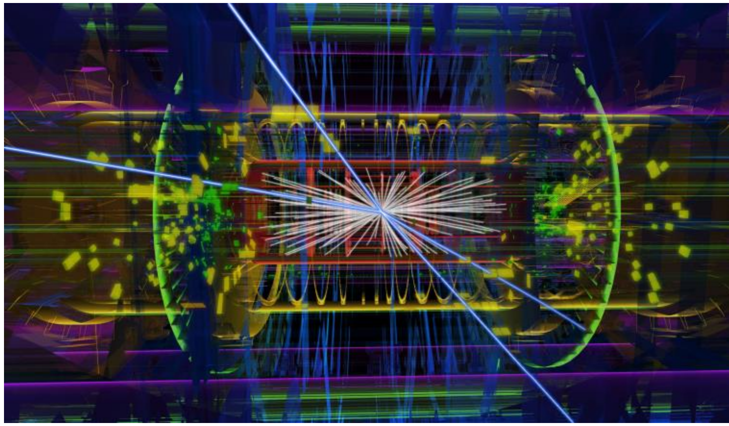


LEP: 88 - 2000





LHC



ATLAS Event

• Particle Detectors •

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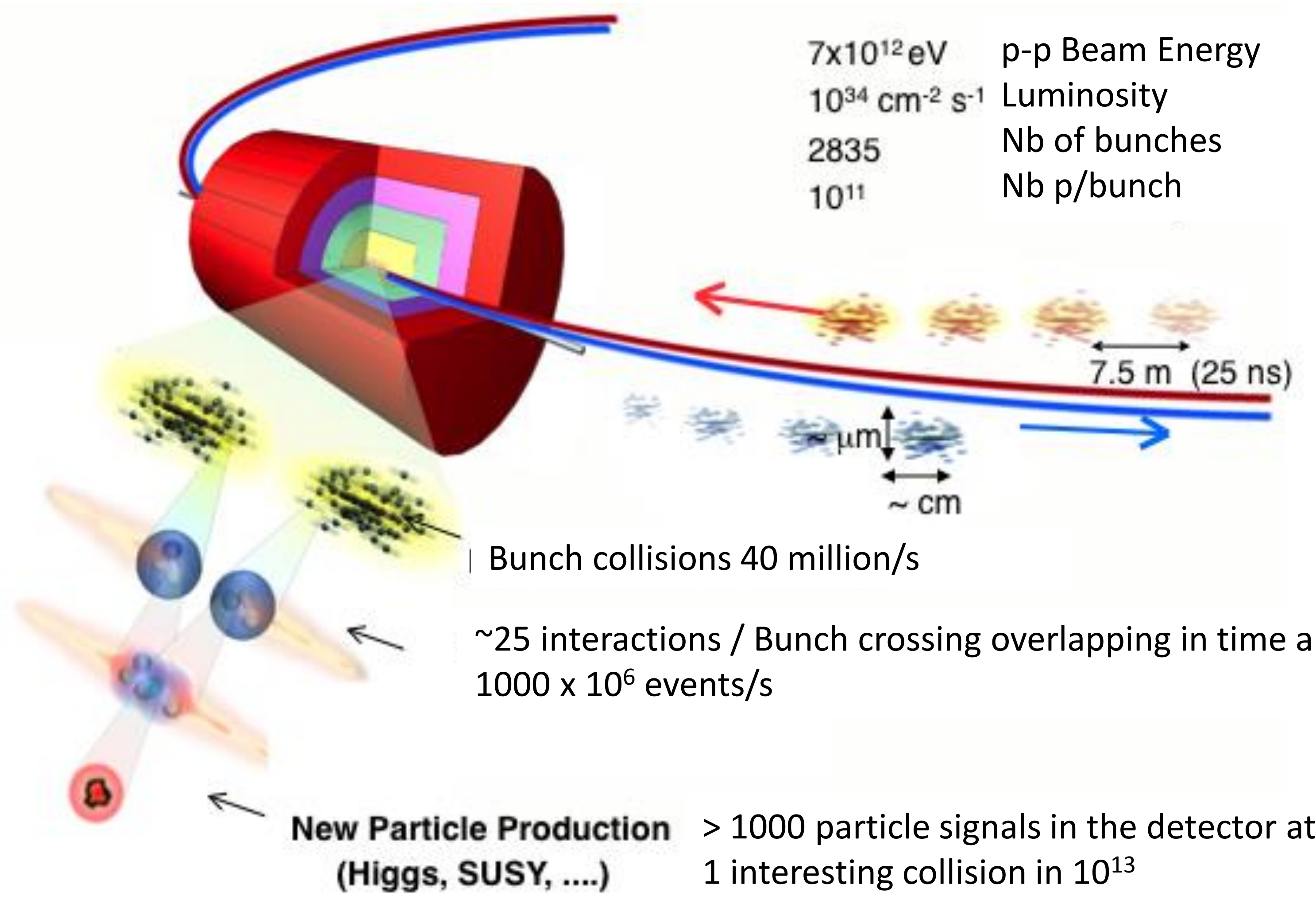
LHC



7×10^{12} eV	p-p Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Nb of bunches
10^{11}	Nb p/bunch

Bunch collisions 40 million/s

~25 interactions / Bunch crossing overlapping in time and space
1000 x 10^6 events/s

> 1000 particle signals in the detector at 40MHz rate
1 interesting collision in 10^{13}

Past VS LHC

Dozens of particles/s		10^9 collisions/s
No event selection	**VS**	Registering 1/10^{12} events
Human analysis		GRID computing

Very Difficult Environment

Slide: M.Nessi, CER

- Bunch crossings every 25 ns …. Fast detector response (ns) …. Bunch crossing identification event by event in order not to mix uncorrelated energy depositions….. Readout at 40 MHz …. 1 Pbytes/sec of data produced

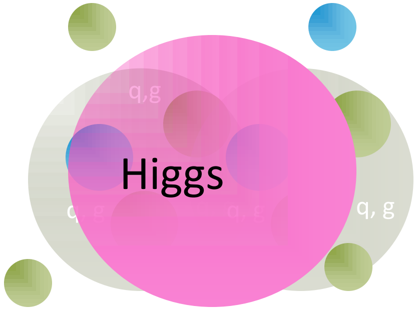
  At each bunch crossing ~ 20 independent events overlap ~ 1000 individual particles to be identified every 25 ns …. Interesting events have large transverse energy …. High density of particles imply high granularity in the detection system … Large quantity of data …. **Large quantity of readout services (100 M channels/active components)**

- **Large neutron fluxes, large photon fluxes** capable of compromising the mechanical properties of materials and of short-circuiting the electronics components and the semiconductors at large

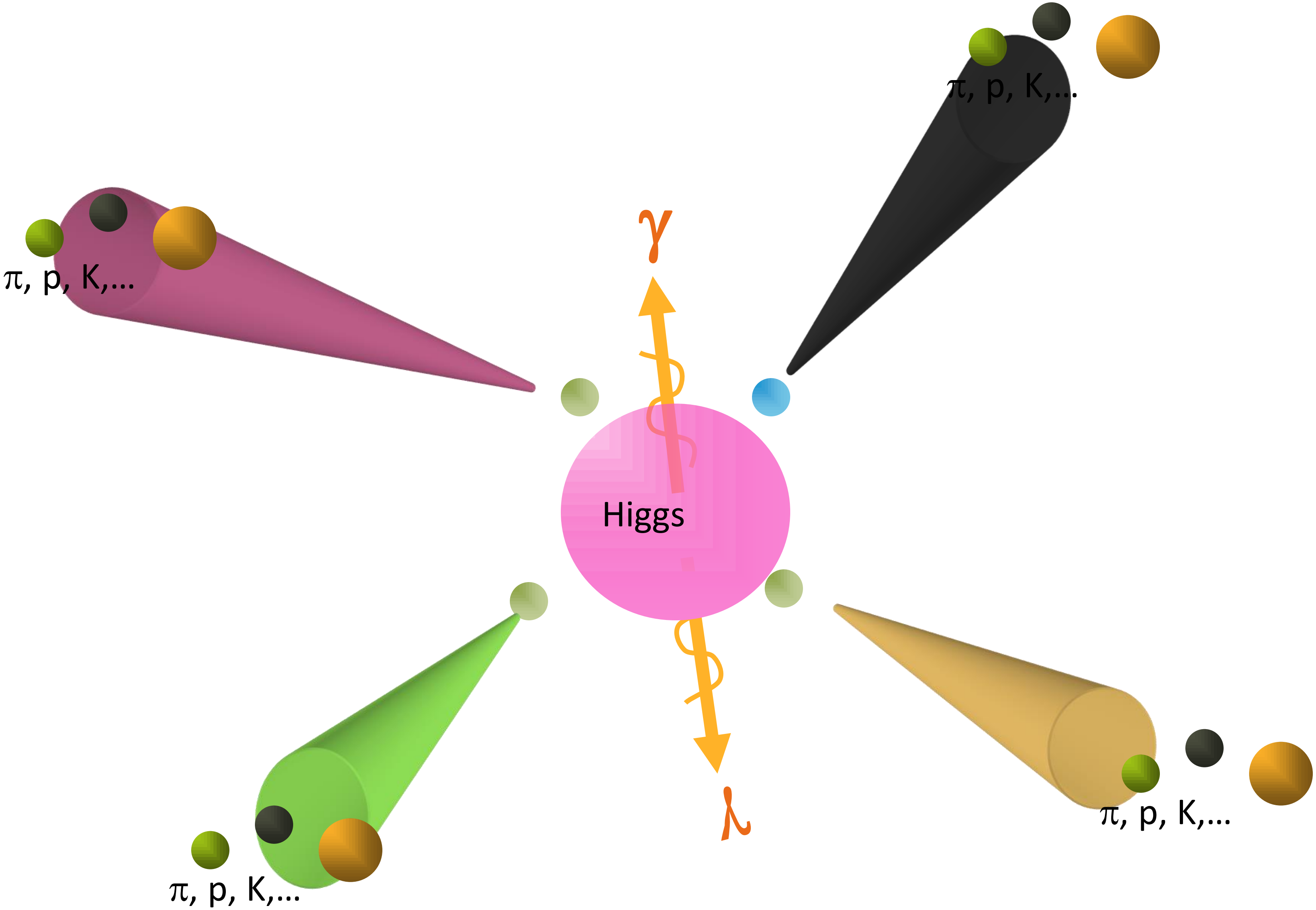
- Large Magnetic Fields in large volumes, which imply usage of **superconductivity (cryogenics)** and attention to **magnetic components** (electronics components, mechanical stress, ….)

- Induced radioactivity in high Z materials (activation) which will add complexity to the **maintenance process**

Artistic Event



Artistic Event



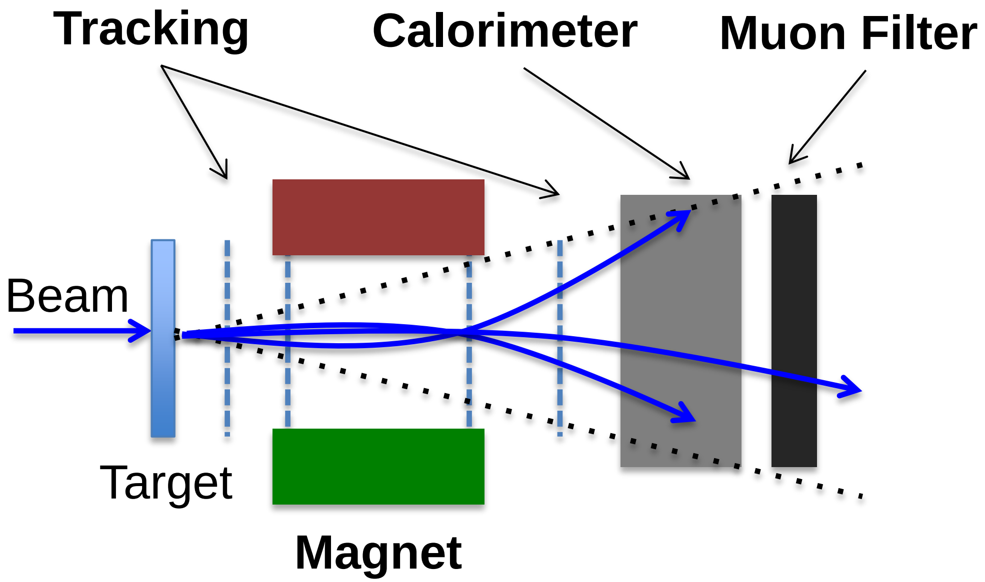
• Particle Detection•

Slide: W.Riegler, CEF

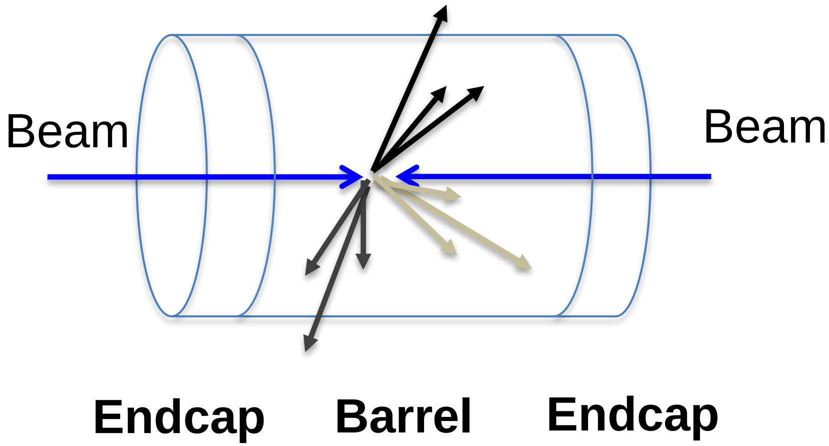
- Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector
- Most of the particles are measured through the decay products and their kinematic relations (invariant mass)
- Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks
- Detectors are built to measure few charged and neutral particles (and their antiparticles) and photons: **$e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, K^o, $p^\pm$, n, ϒ**
- Their difference in mass, charge and interaction is the key to their identification

• Detector Systems •

Fix Target Geometry



Collider Geometry



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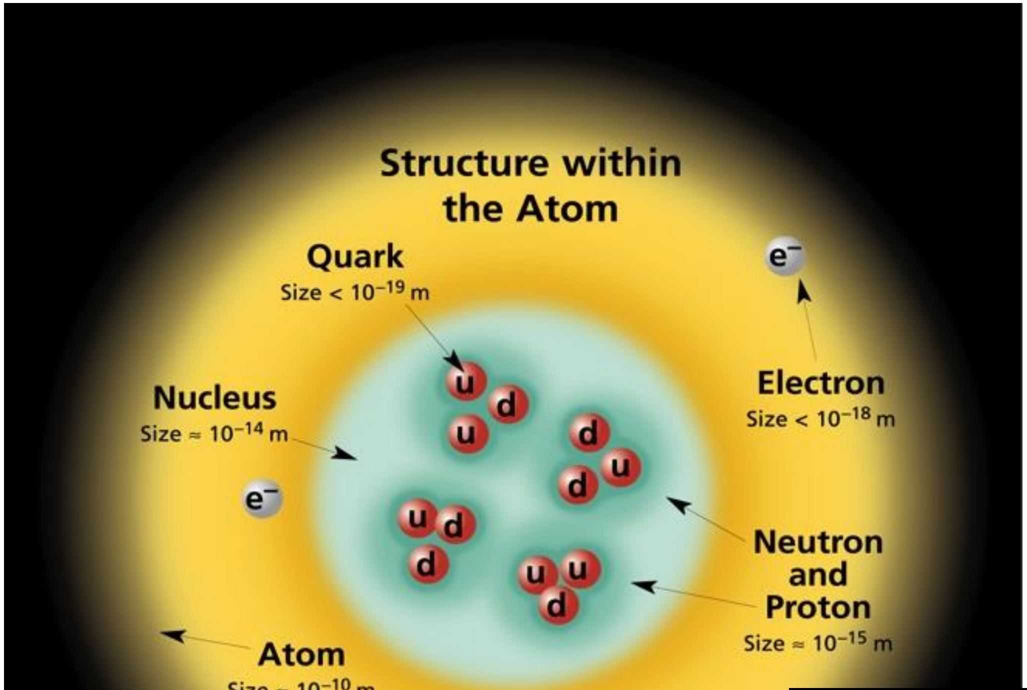
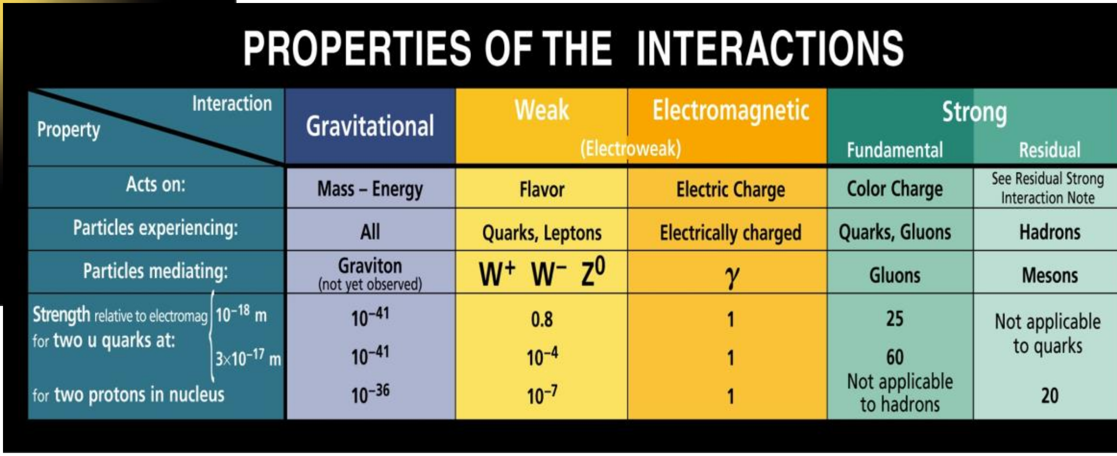
• Interactions•



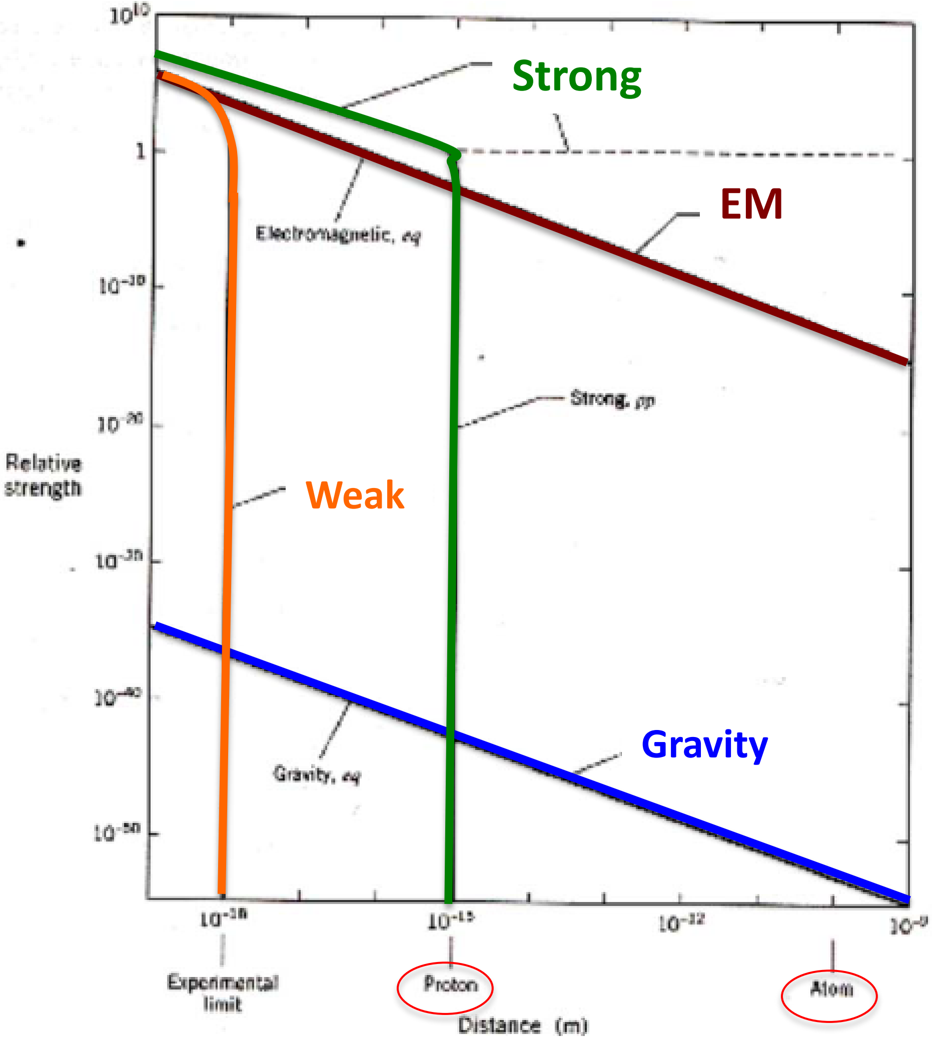
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Forces VS Distance



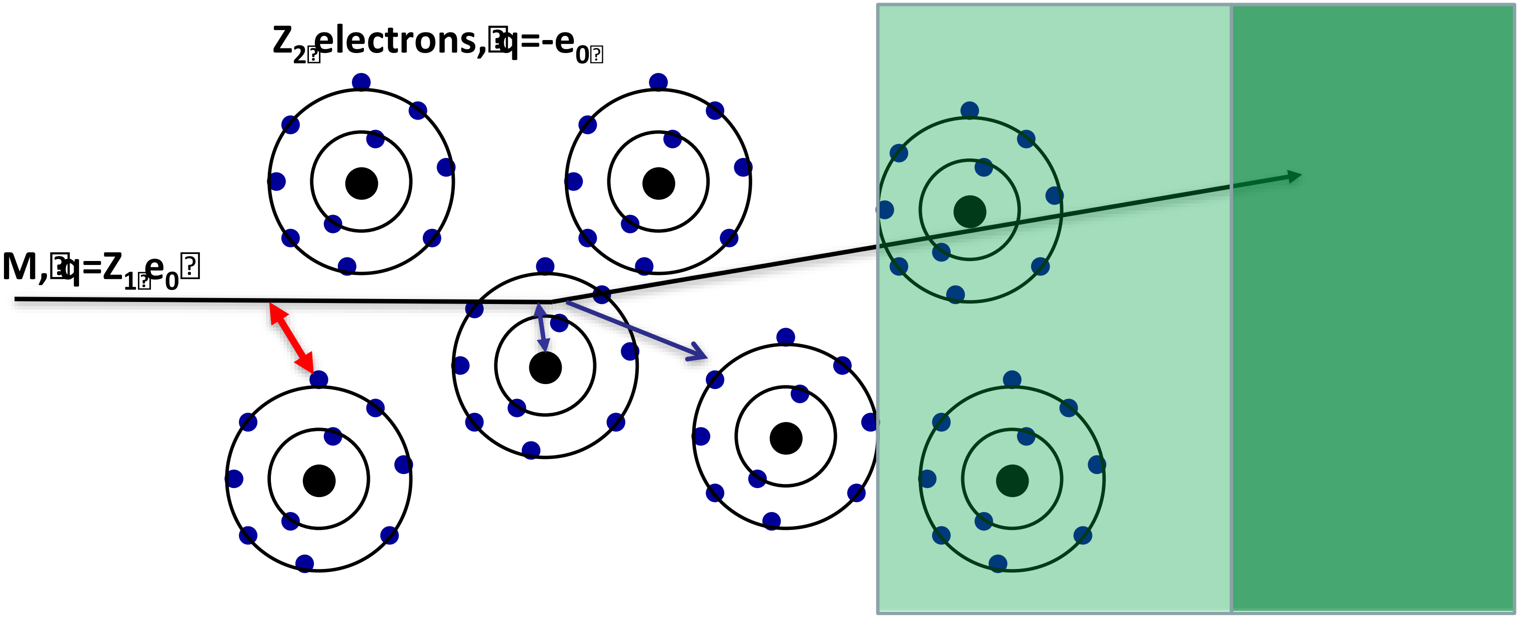
- **Atomic distances**: Only EM and Gravity have sizable strengths.

  EM is 40 orders of magnitude stronger than G

- At **proton distances**, the Strong Force turns on and becomes 100 times stronger than EM
- At **distances 1/1000 of proton size**, the Weak Force turns on abruptly

EM Interaction of Particles

Slide: W.Riegler, CERN



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

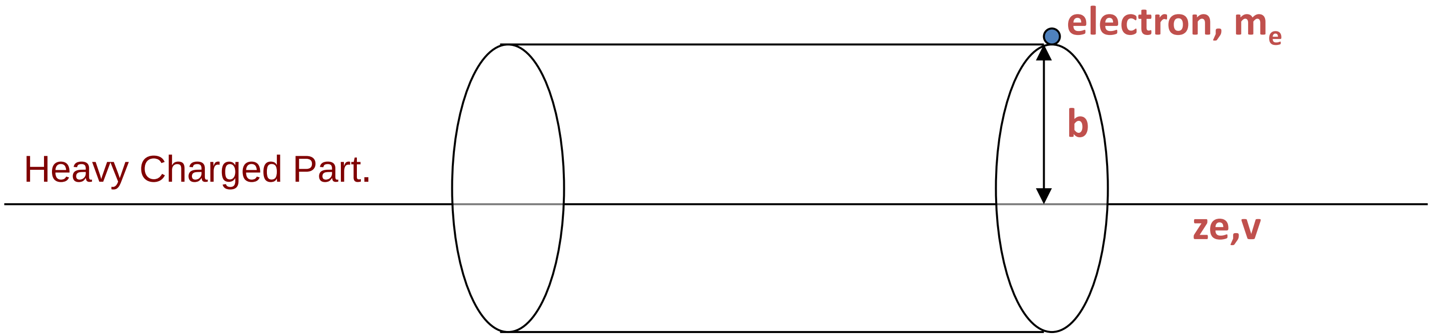
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Heavy Charged Particles

- Heavy charged particles transfer energy mostly to the atomic electrons. We will later come back to not so heavy particles: electrons/positrons

- Usually the Bethe Bloch formally is used to describe this - and most of features of the Bethe Bloch formula can be understood from a very simple model :

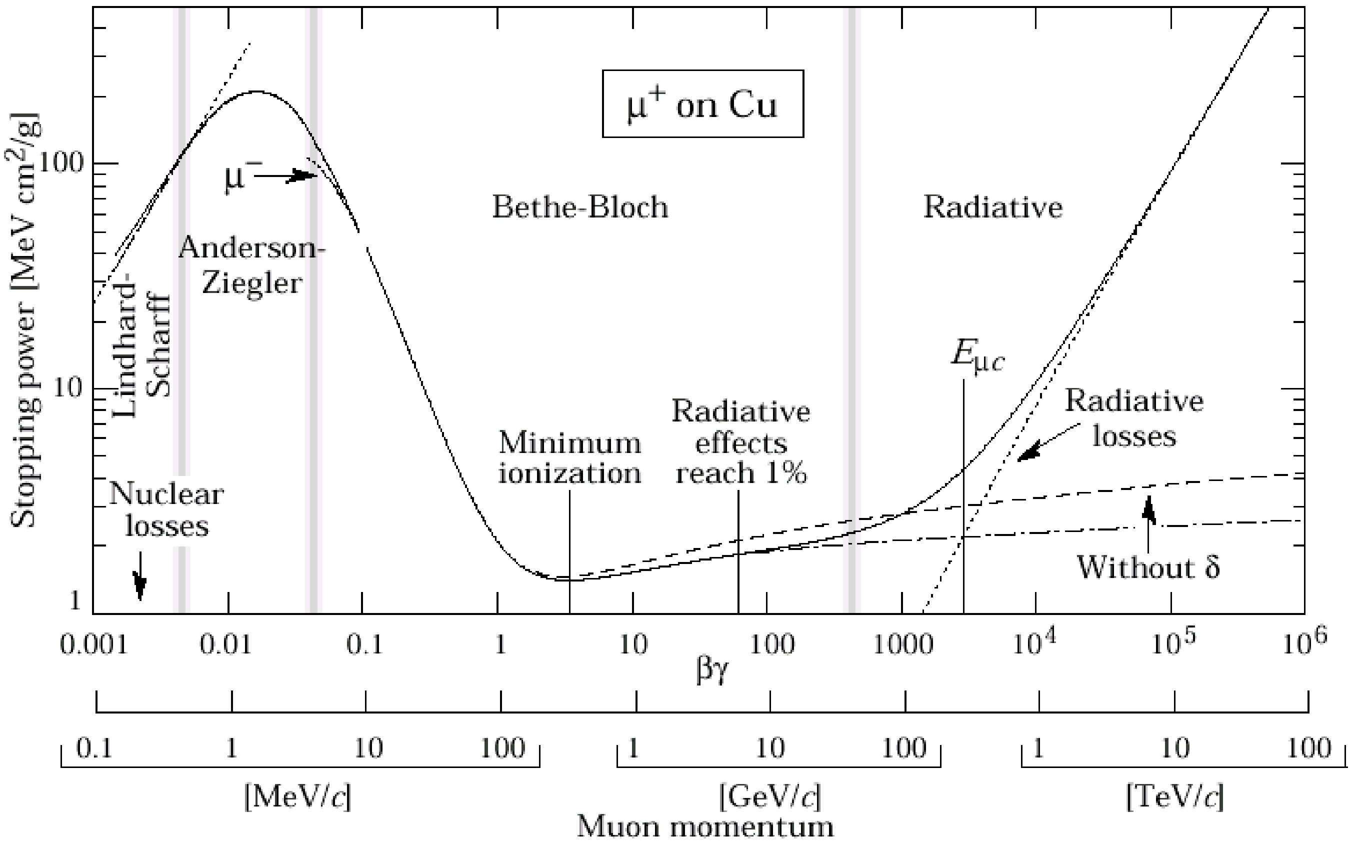
  1. Let us look at energy transfer to a single e- from heavy charged particle passing at a distance b
  2. Let us multiply with the number of electrons passed (~ Z)
  3. Let us integrate over all reasonable distances b



Heavy Charged Particles

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

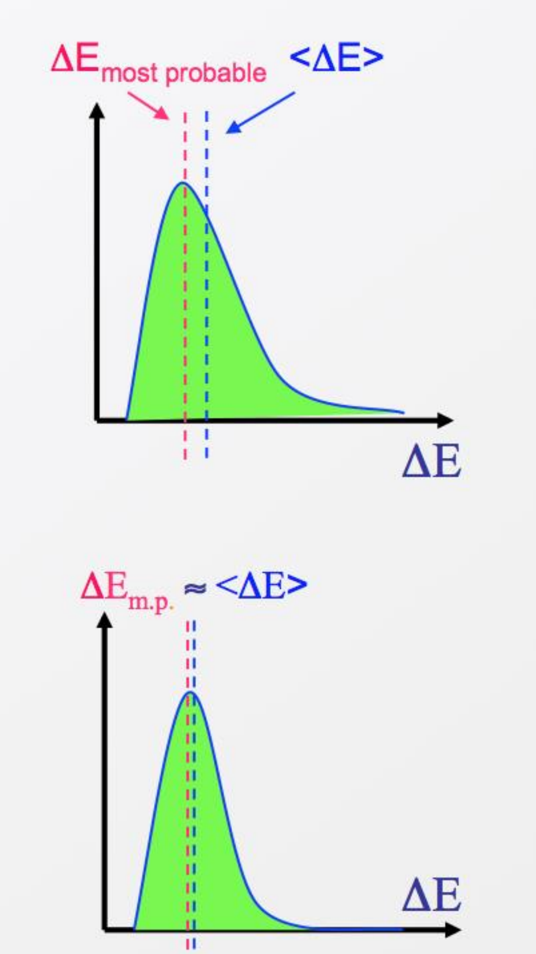
N: Avogadro’s Nb
m_e: e- mass
Z, A: medium Atomic, Mass
I: effective ionization potent
B: projectile velocity



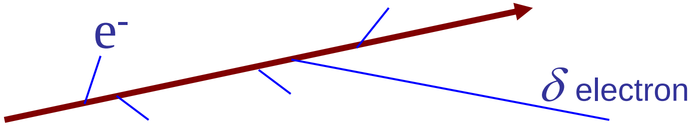
Heavy Charged Particles

Real detector (limited granularity) can not measure <*dE/dx*>

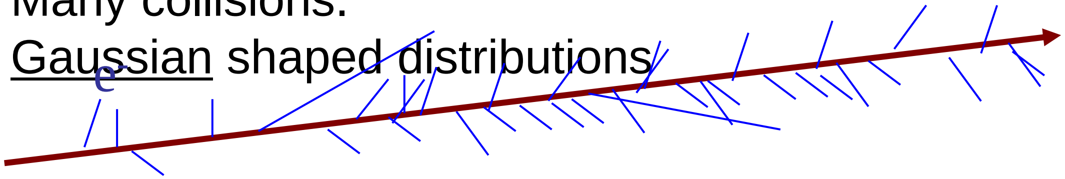
It measures the energy *ΔE* deposited in a layer of finite thickness δx



For thin layers or low density materials:
Few collisions, some with high energy transfer.
Energy loss distributions show large fluctuations towards high losses: Landau tails

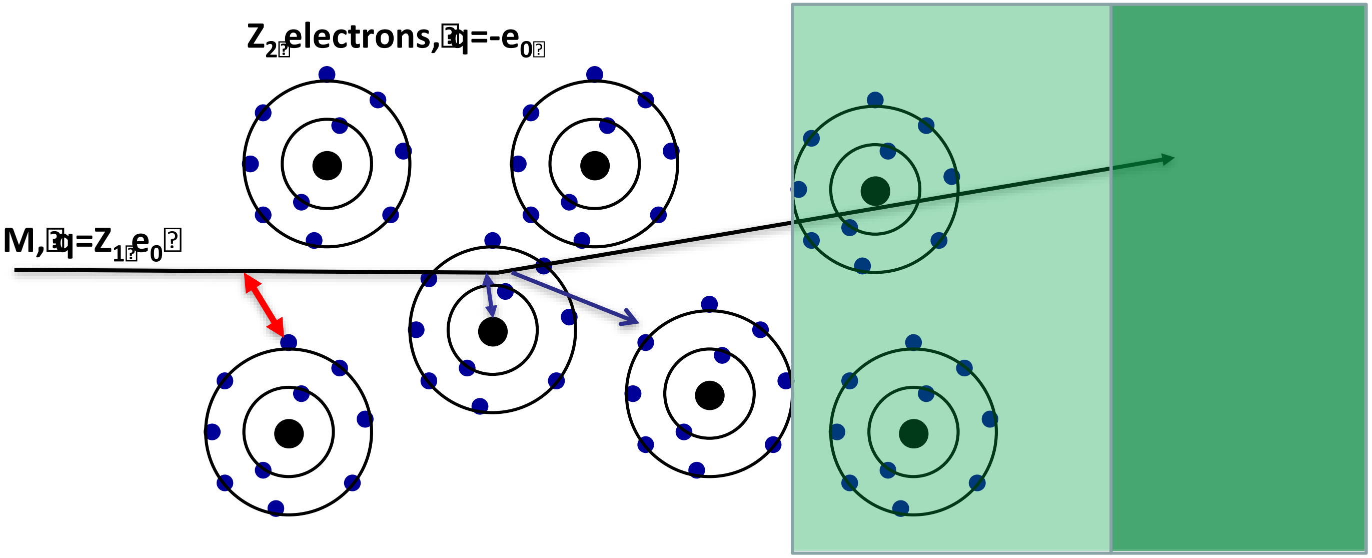


For thick layers and high density materials:
Many collisions.
Gaussian shaped distributions



EM Interaction of Particles

Slide: W.Riegler, CERN



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

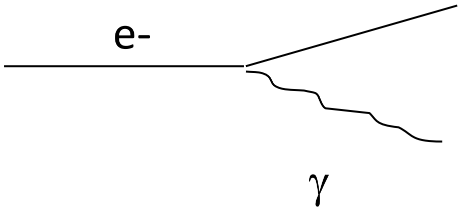
Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

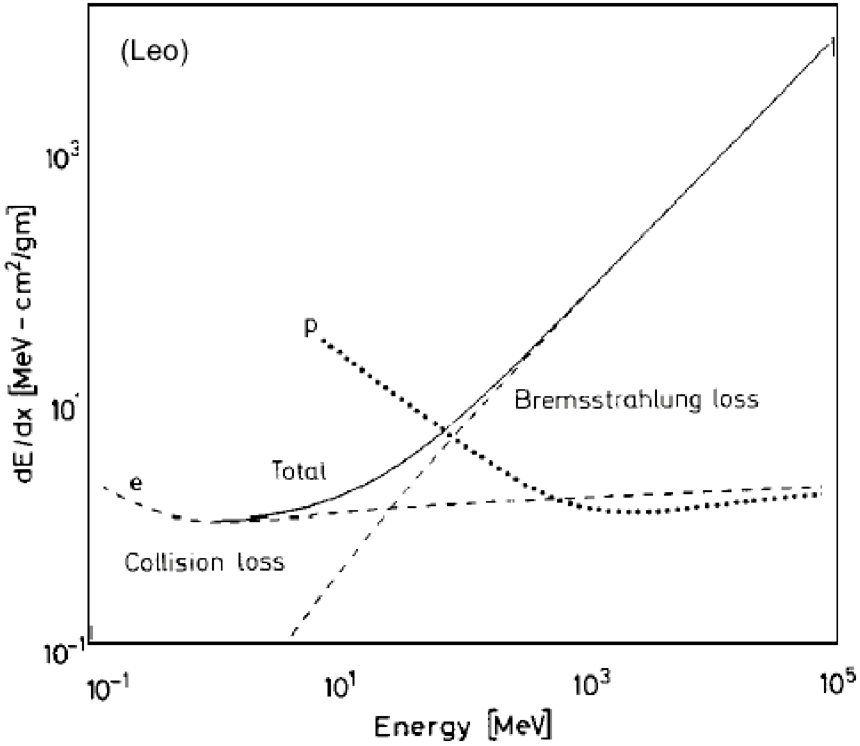
Electrons and Positrons

- Electrons/positrons; modify Bethe Bloch to take into account that incoming particle has same mass as the atomic electrons

- Bremsstrahlung in the electrical field of a charge Z comes in addition : □ goes as $1/m^2$



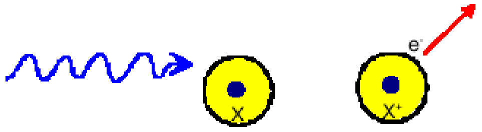
Deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus



Neutral Particles

- **Photoelectric effect (Z^5)**; absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.

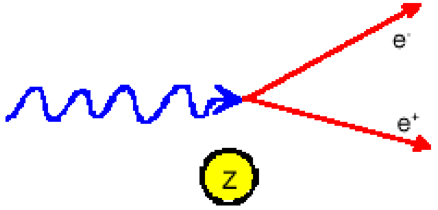
  Used in various detector technologies (very imp. In medical imaging)



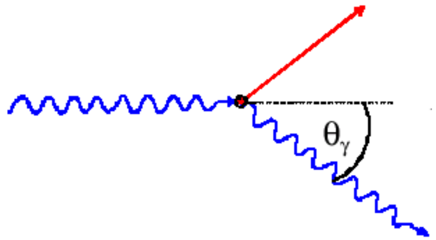
$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

- **Pair-production (Z^2+Z)**; essentially bremsstrahlung; threshold at 2 m_e = 1.022 MeV. Dominates at a high energy.

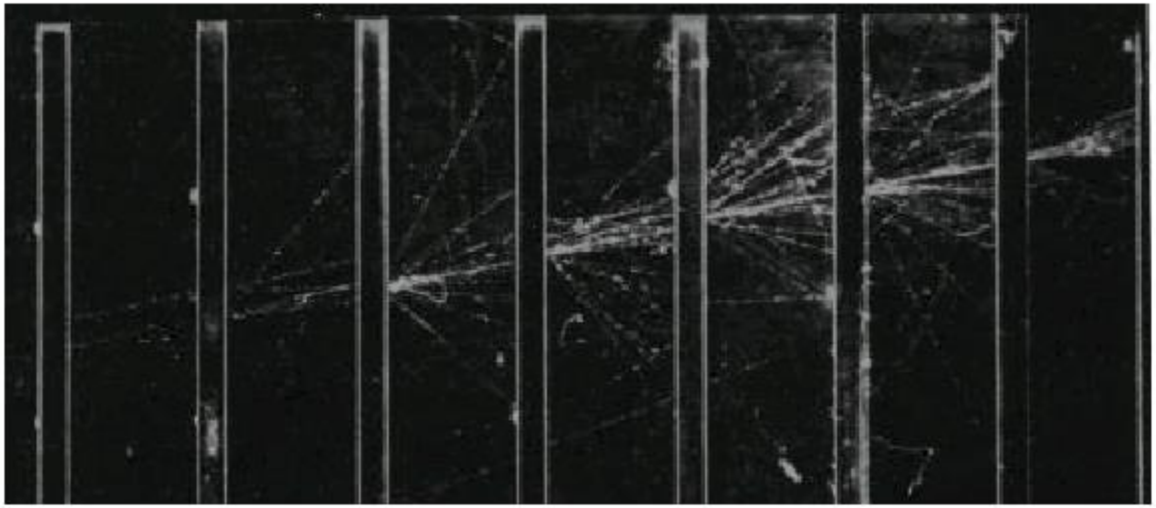
  Most important in our field, Initiates EM shower in calorimeters



- **Compton scattering (Z)**; scattering of a photon against a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc) and for energies above a few MeV 90% of the energy is transferred (in most cases).

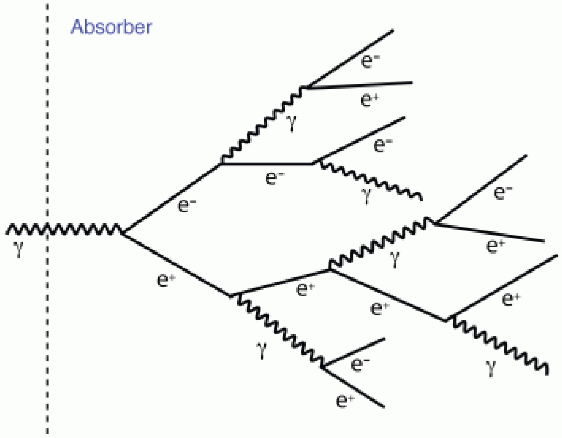


EM Calorimeter



Electron shower in a cloud chamber with lead absorbers

Considering only Bremsstrahlung and Pair Production with one splitting per radiation length (either Brems or Pair) we can extract a good mode for EM showers



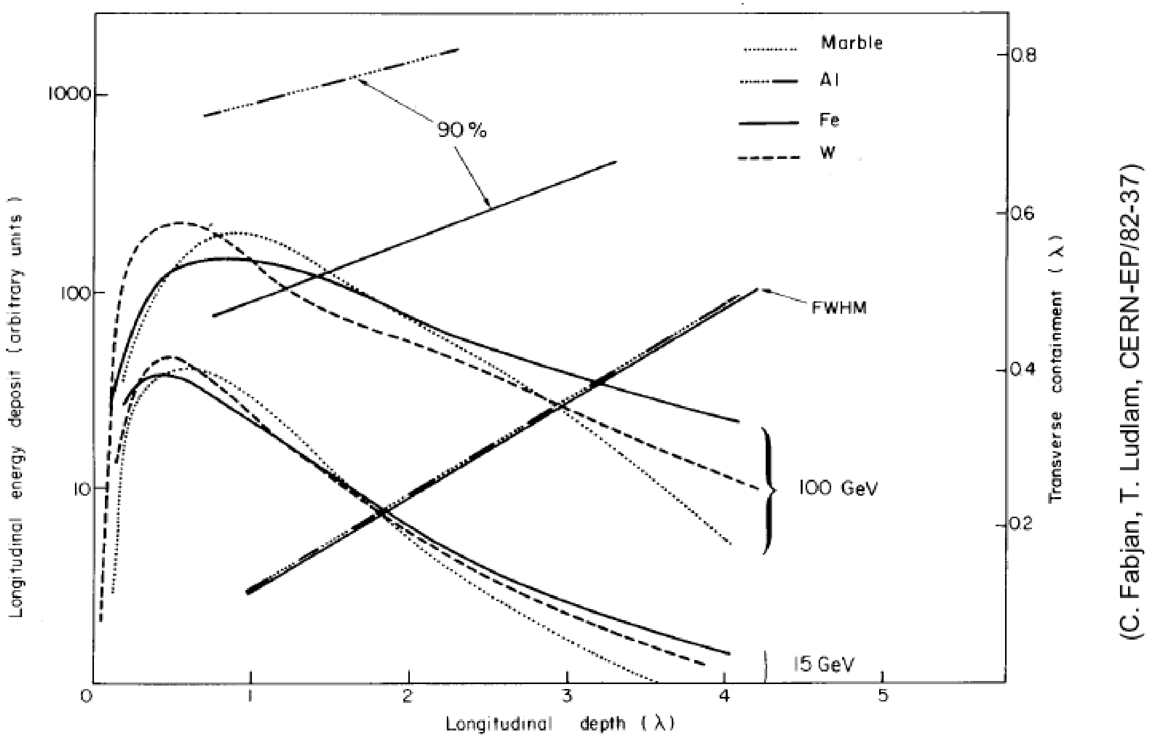
Hadronic Calorimeter

Longitudinal shower development

$$t_{\max}(\lambda_I) \approx 0.2 \ln E[GeV] + 0.7$$

$$t_{95\%} \approx a \ln E + b$$

For Iron: a = 9.4, b=39
E =100 GeV
→ $t_{95\%} \approx$ 80 cm



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Additional strong interactions for hadrons (p,n, etc); hadronic absorption/interaction length and hadronic showers

Neutrinos

- Neutrinos interact only weakly, tiny cross-sections
- To detect neutrinos, we need first a charged particle (again)
  - Possible reactions:

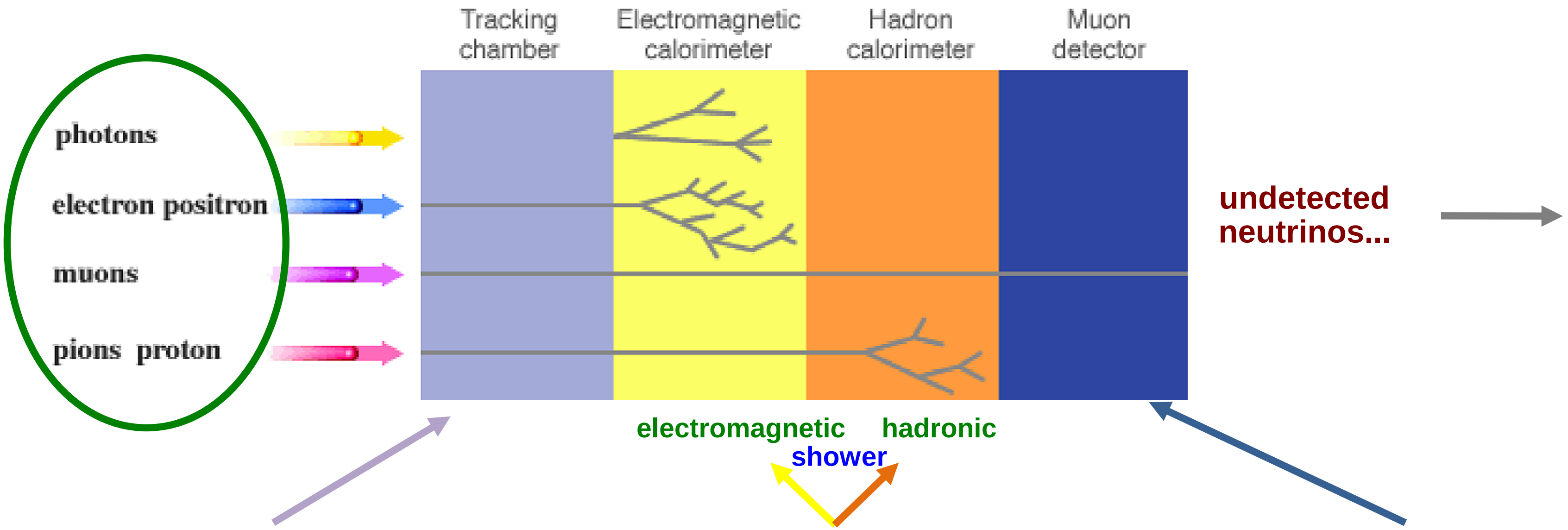
$$\nu_\ell + n \rightarrow \ell^- + p \qquad \ell = e,\ \mu,\ \tau$$

$$\bar{\nu}_\ell + p \rightarrow \ell^+ + n \qquad \ell = e,\ \mu,\ \tau$$

- The cross-section or the reaction $\boldsymbol{\nu_e + n \rightarrow e^- + p}$ is of the order 10^{-43} cm^2 (per nucleon, E_n ~ few MeV), therefore
  - Detection efficiency $\varepsilon_{det} = \sigma \times N^{surf} = \sigma\, \rho\, N_A\, d / A$
  - 1m Iron: $\varepsilon_{det} \sim 5 \times 10^{-17}$
- Neutrino detection requires big and massive detectors (kT) and high neutrino fluxes
- In collider experiments, fully hermetic detector allow to detect neutrinos indirectly: we sum up all visible energy and momentum, and attribute missing energy and momentum to neutrino

• Interactions in the Detector•

Low density → High density
High precision → Low precision
High granularity → Low granularity



undetected neutrinos...

electromagnetic hadronic
shower

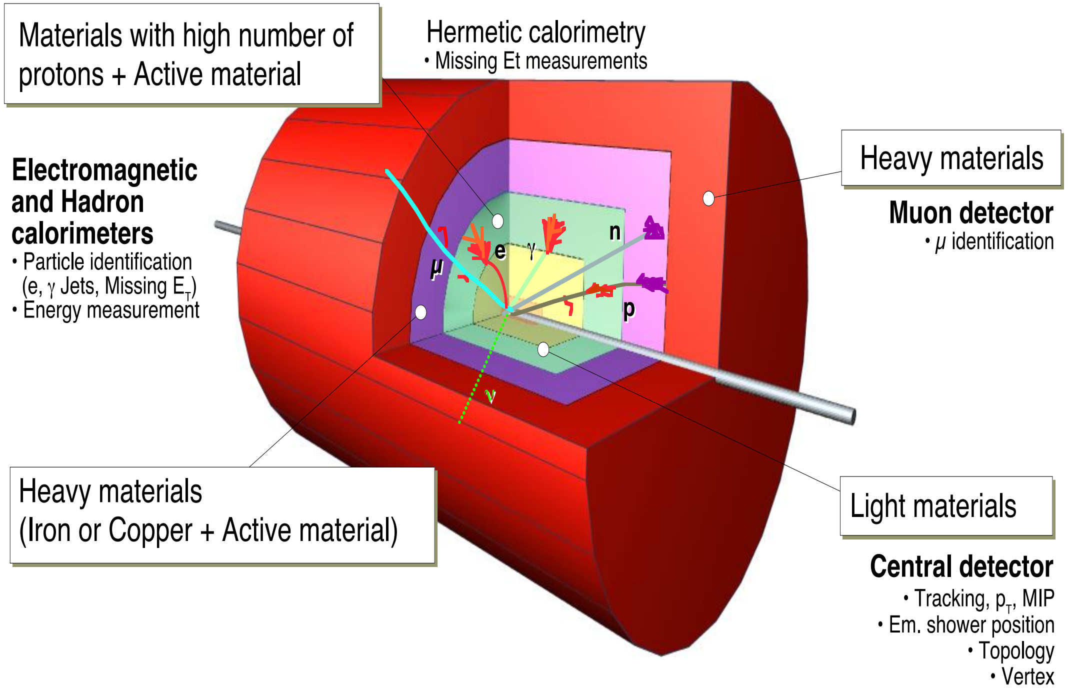
momentum measurement
by curvature in magnetic field

energy measurement
by creation and total absorption of showers

muon detection with improved momentum measurement (long lever arm)

• Detector Systems •

Slide: M.Nessi, CERN



Materials with high number of protons + Active material

Hermetic calorimetry
- Missing Et measurements

Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing E_T)
- Energy measurement

Heavy materials

Muon detector
- μ identification

Heavy materials (Iron or Copper + Active material)

Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

- Hermetic coverage down to the beam pipe (few cm), in order to measure all the transverse energy flow to allow transverse missing energy identification
- Large Magnetic Fields capable of bending trajectories of ~100 GeV charged particles by mm (sagitta) ~ 1-4 Tesla Fields
- Trackers and Calorimeters capable of 1% momentum/energy resolution, high space granularity for particle identification and position resolution and low occupancy
- **Many detection techniques available, chosen based on precision, fast response, particle ID capability, radiation resistance…**
- **Careful choice of material distribution:** very low near to the beam pipe (inner detector), enough material to contain EM and HAD showers in the calorimeters, radiation background (n, g) moderation/absorption in the muon spectrometer

• Summary •

Slide: W.Riegler, CERN

- **Ionization and Excitation:**
  - Charged particles traversing material are exciting and ionizing the atoms
  - The average energy loss of the incoming particle by this process is to a good approximation described by the Bethe Bloch formula
  - The energy loss fluctuation is well approximated by the Landau distribution

- **Multiple Scattering and Bremsstrahlung:**
  - The incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons
  - Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer
  - The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus, which causes an EM cascade. This effect depends on the 2nd power of the particle mass, so it is only relevant for electrons

• Particle Detectors •

OUTLINE

1. Historical Overview
2. Particle Detector Challenges at LHC
3. Interactions of Particles with Matter
4. **Detector Technologies**
5. How HEP Experiments Work

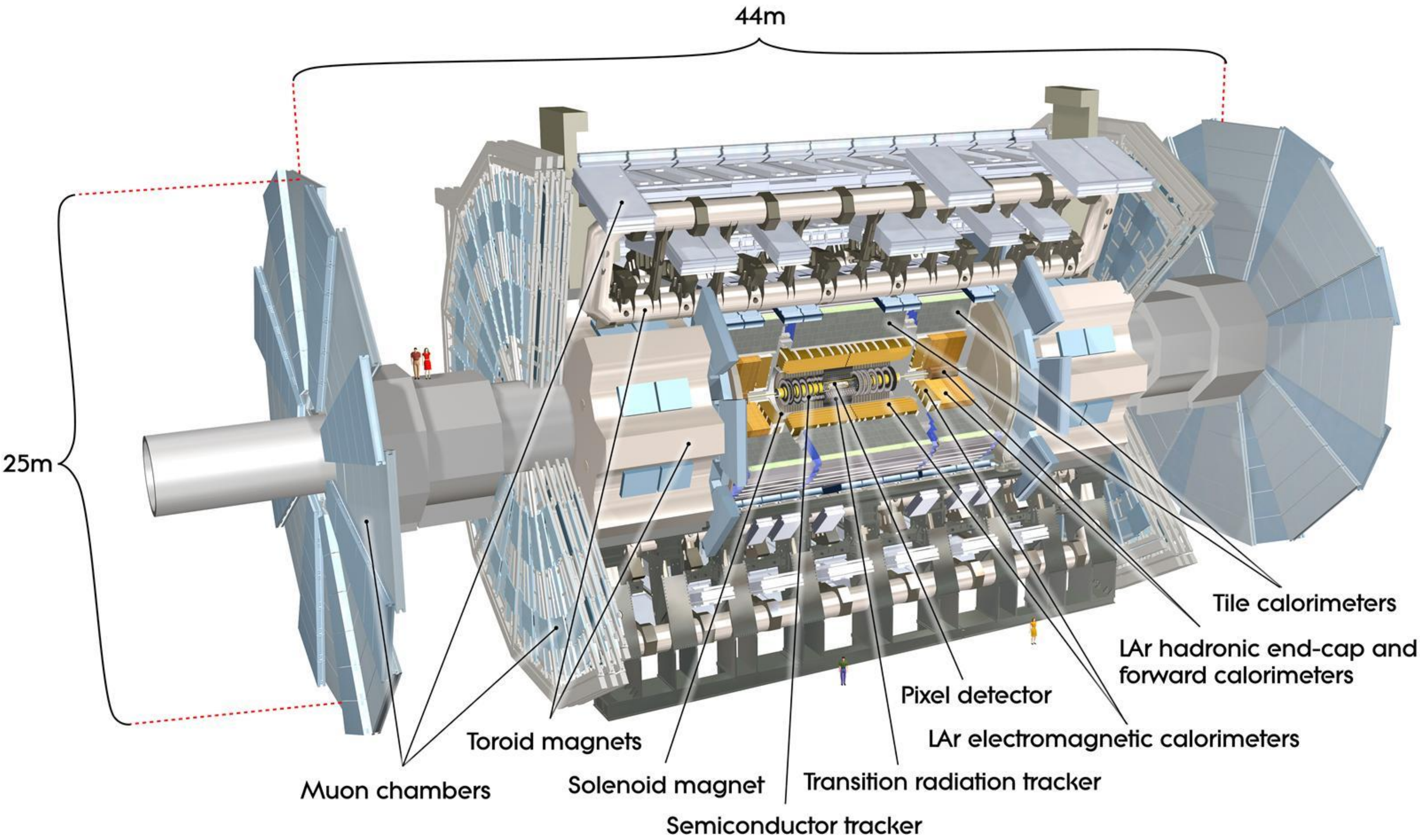
Detector Technologies

- How are reactions of the various particles with detectors turned into electrical signals. We would like to extract position and energy information channel by channel from our detectors.
- Three effects/technologies are usually used :
  1. Ionisation
  2. Semiconductors
  3. Scintillation

and these are used in either for tracking (and triggering), energy measurements, photon detectors for Cherenkov or TRT, etc

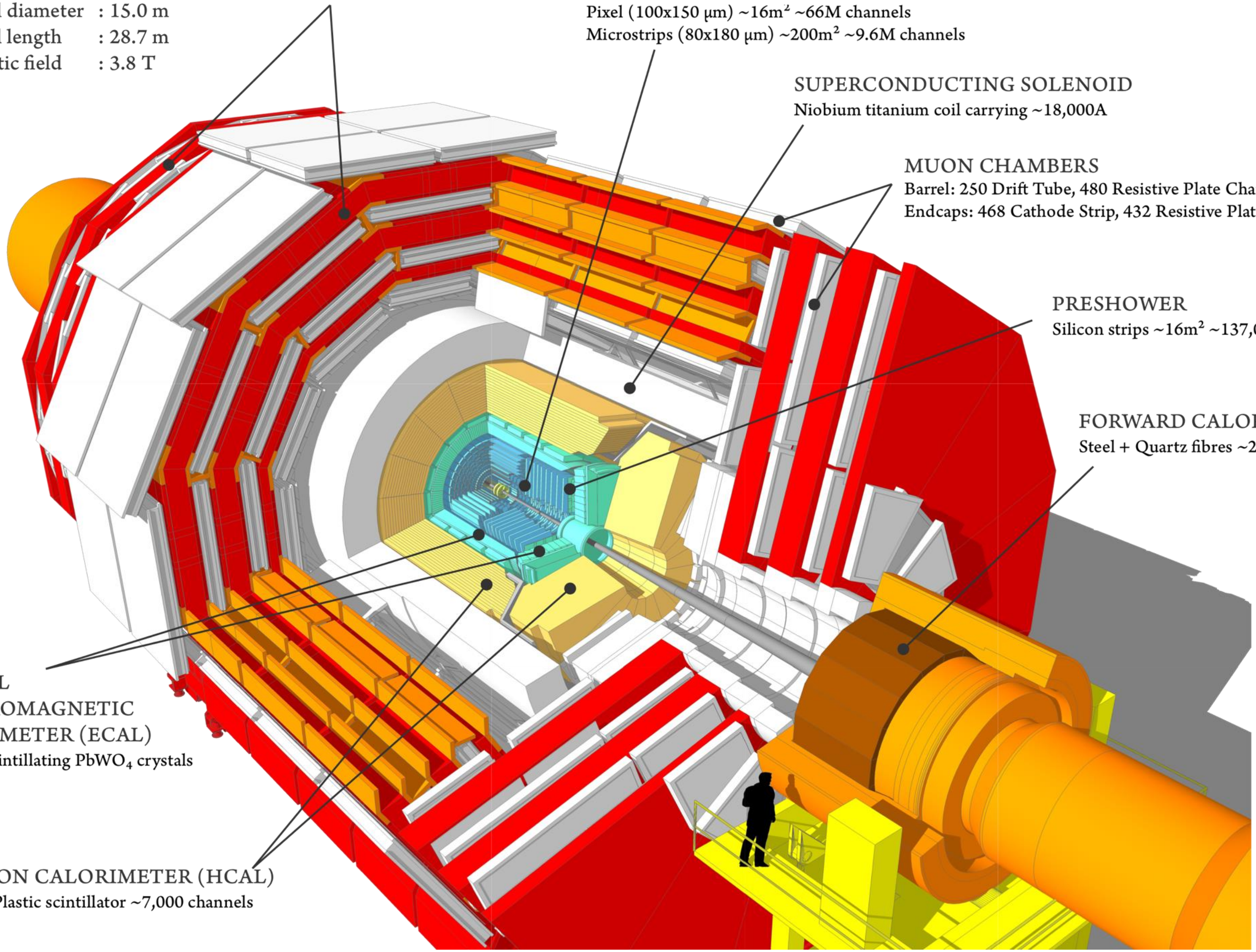
and from then on, it is all online (trigger, DAQ) and offline treatment and analysis ….

ATLAS Detector



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

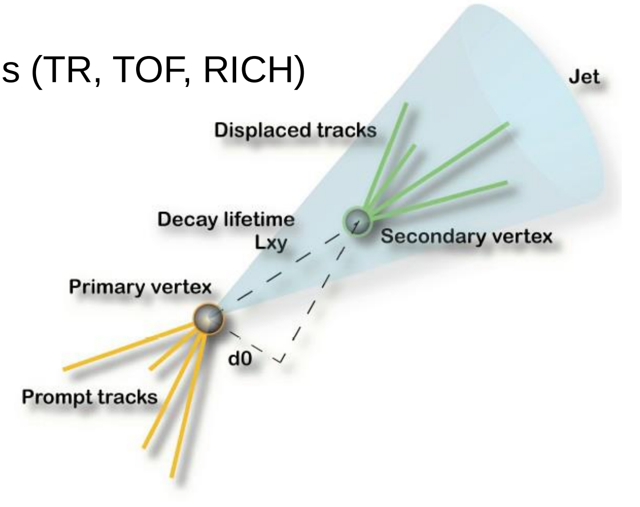
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Trackers

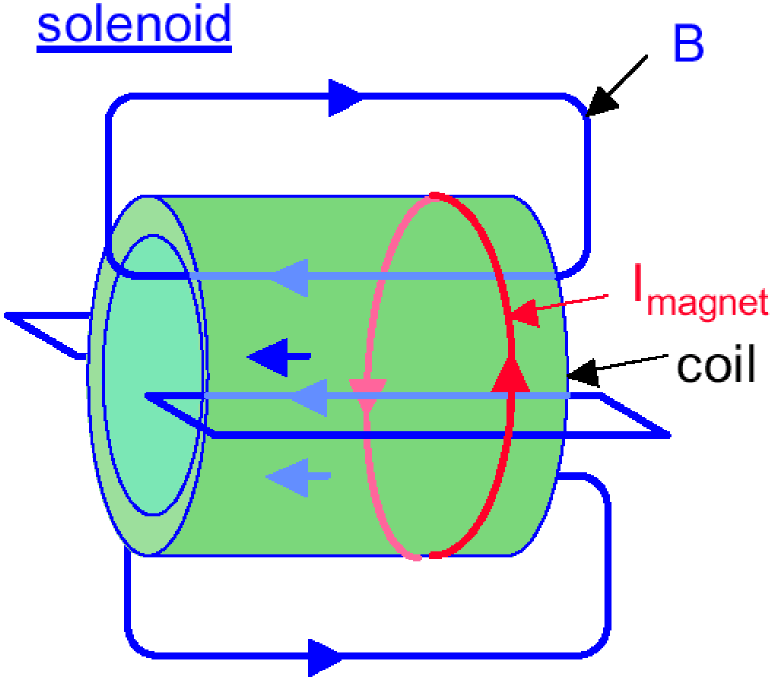
- Measure charged particles as they emerge from the interaction point, disturbing them as little as possible
- Measure the trajectory of charged particles
  - Measure several points (hits) along the track and fit curves to the hits (helix, straight line)
- Determine their momentum
  - From their curvature in a magnetic field
- Extrapolate back to the point of origin
  - Reconstruct primary vertices
- Reconstruct secondary vertices
  - Long-lived particles have a measurable displacement between primary vertex and decay
- Match tracks with showers in the calorimeters or tracks in the muon systems
- Trackers also contribute to particle identification (PID)
  - Measuring rate of energy loss (dE/dx) in the tracker
  - Using dedicated detectors to distinguish different particle types (TR, TOF, RICH)

Want a compact detector, inside a magnetic field, to register as many hits as possible but light to minimise interactions of charged (and neutral) particles before they reach the calorimeter systems



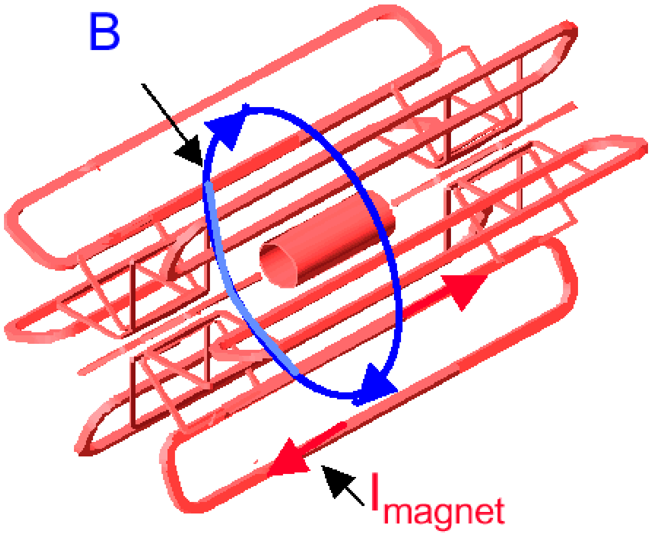
• Magnetic Fields •

solenoid



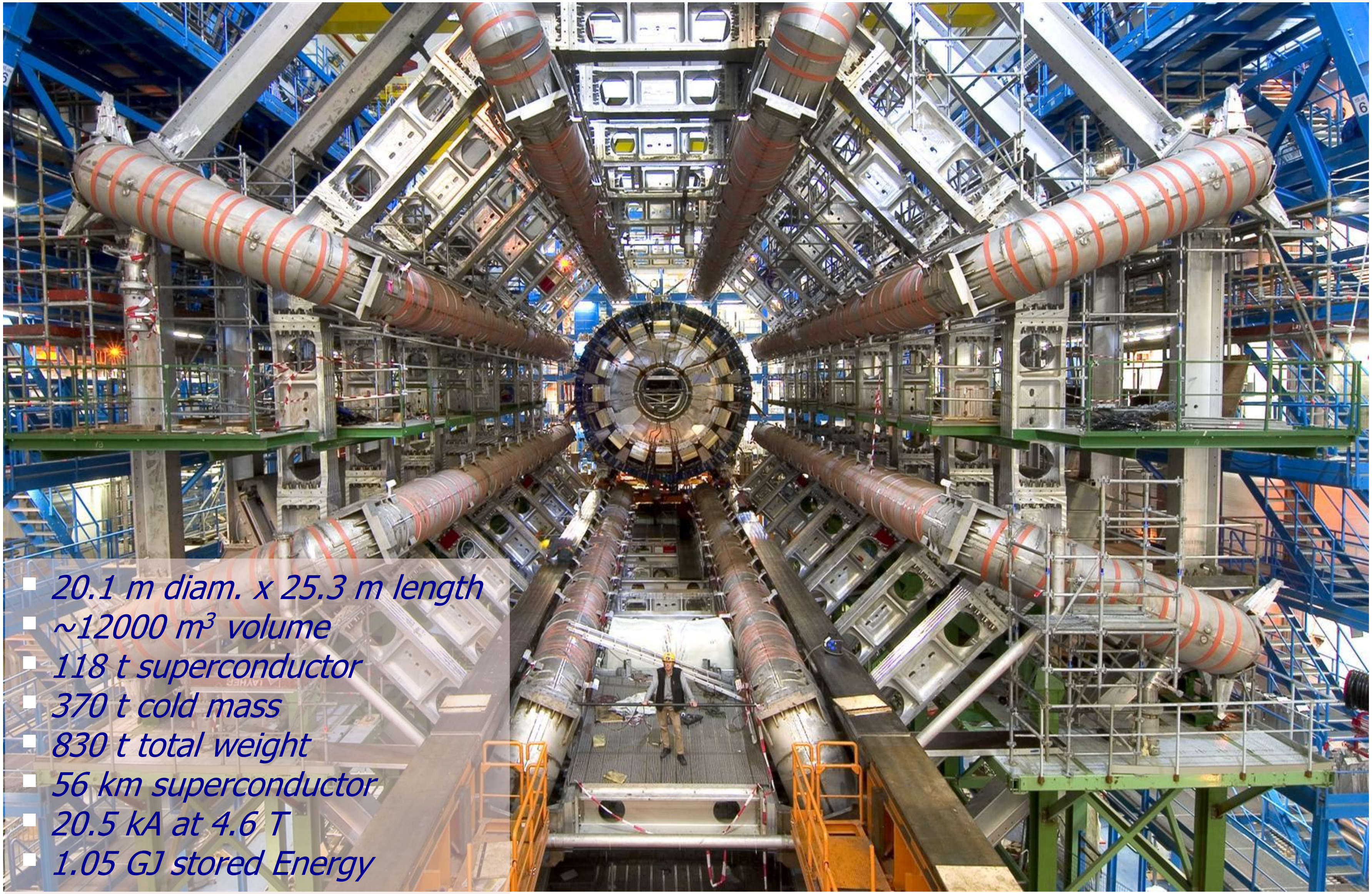
+ Large homogenous field inside coil
- Weak opposite field in return yoke
- Size limited (cost)
- Rel. high material budget

toroid



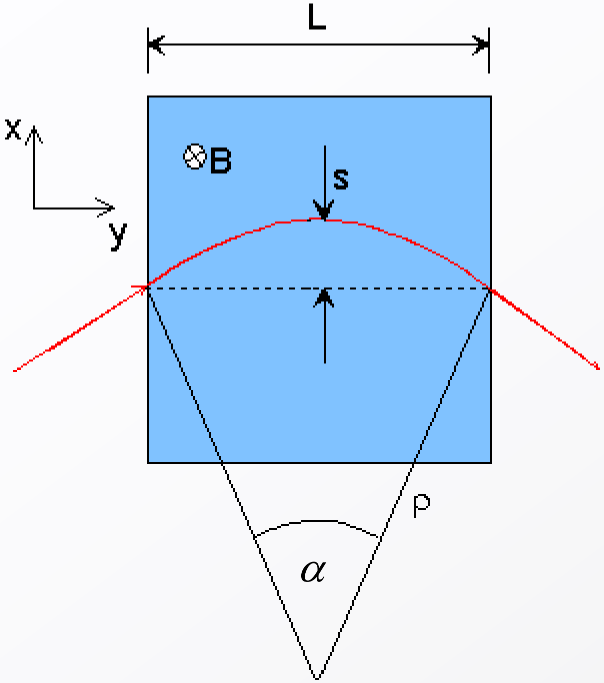
+ Field always perpendicular to p
+ Rel. large fields over large volume
+ No return yoke needed
+ Rel. low material budget
- Non-uniform field
- Complex structure

• ATAS Toroidal Magnet •



- *20.1 m diam. x 25.3 m length*
- *~12000 m^3 volume*
- *118 t superconductor*
- *370 t cold mass*
- *830 t total weight*
- *56 km superconductor*
- *20.5 kA at 4.6 T*
- *1.05 GJ stored Energy*

Momentum measurement



We measure only p-component transverse to B field !

$$p_T = qB\rho \qquad \rightarrow \qquad p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\alpha/2 \approx \alpha/2 \qquad \rightarrow \qquad \alpha \approx \frac{0.3L\cdot B}{p_T}$$

$$s = \rho(1-\cos\alpha/2) \approx \rho\frac{\alpha^2}{8} \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

the sagitta s is determined by 3 measurements with error *σ(x):*

$$s = x_2 - \frac{x_1+x_3}{2} \qquad \left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\,\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\,\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$

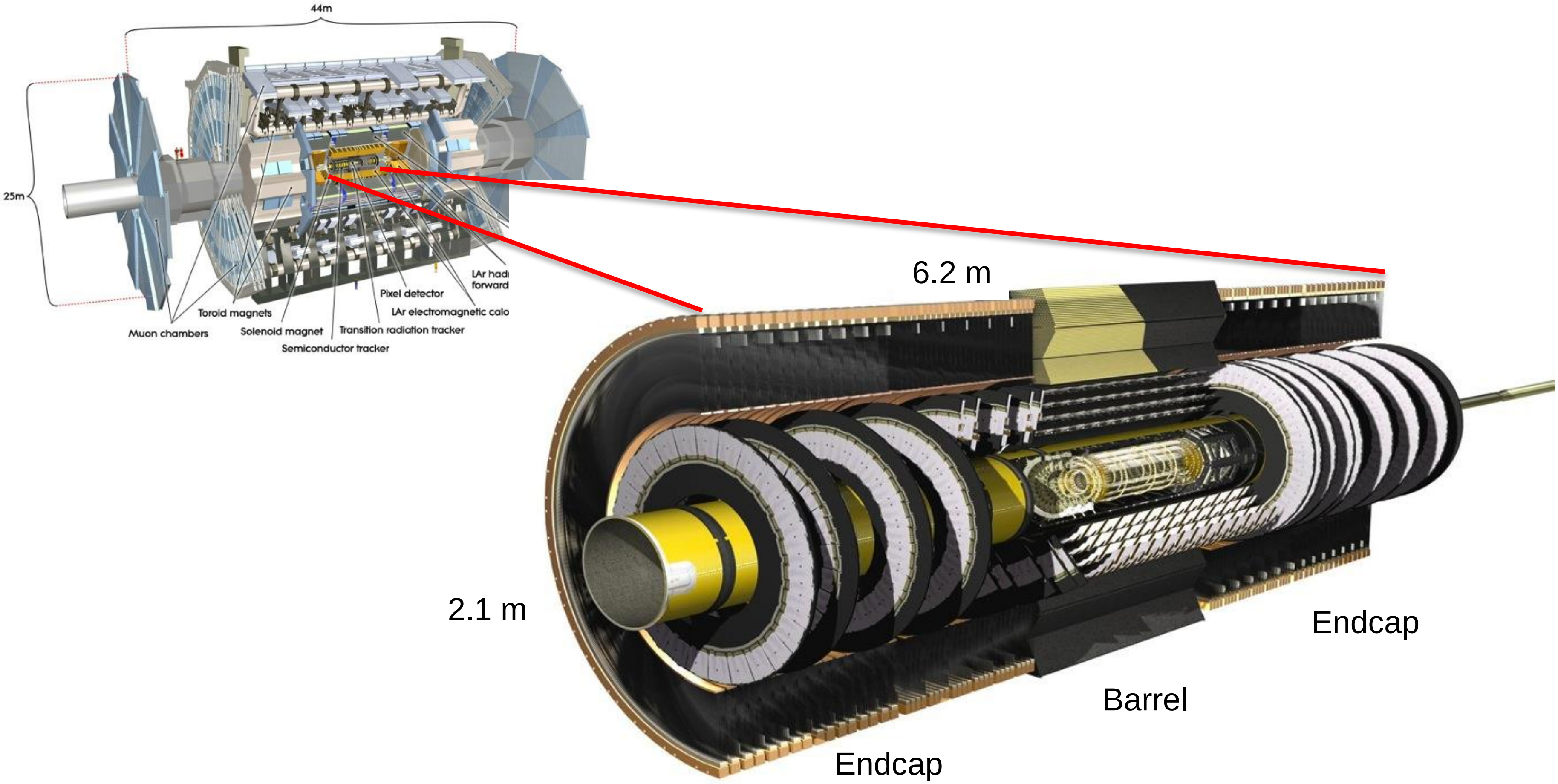
$$\boxed{\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \propto \frac{\sigma(x)\cdot p_T}{BL^2}}$$

for N equidistant measurements, one obtains (R.L. Gluckstern, NIM 24 (1963) 381)

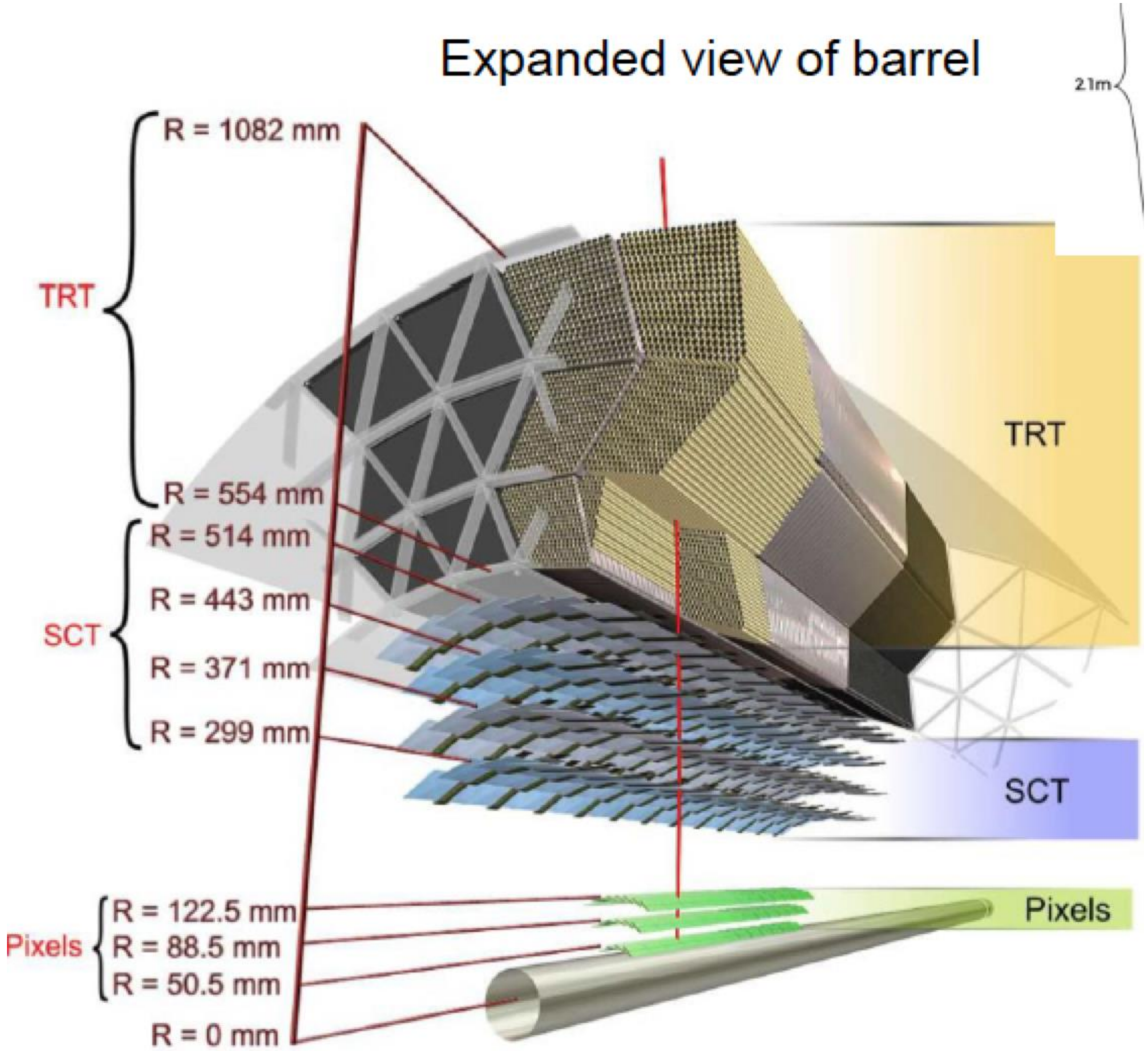
$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

(for N ≥ ~10)

ATLAS Tracker



ATLAS Tracker



TRT (Straws-Gas)
350 kchannels
36 track points
σ ~130 mm

SCT (Silicon strips)
6.2 Mchannels
4 track points
σ ~16 mm

Pixel (Silicon pixels)
80 Mchannels
3 track points
σ ~10 mm

• Gaseous Detectors •

- Let’s look in some detail to this particular technology
- Thus, back to the principle of particle detection in a gaseous or condensed medium

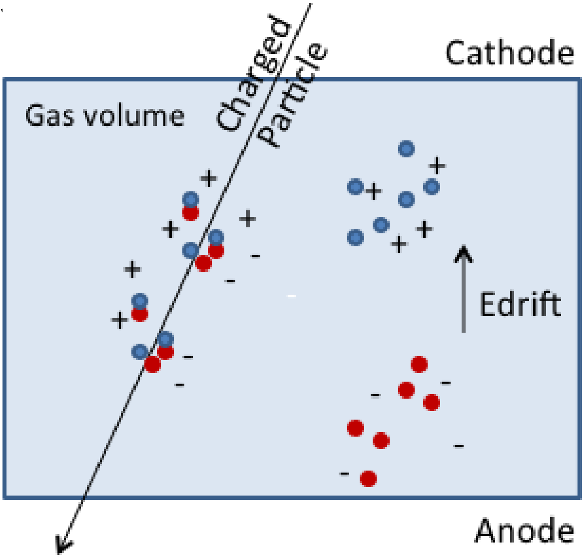
  where only EM interaction is generally used as basis for detection; it concerns Coulomb interactions between the EM fields of the incoming charged particle and of the medium, resulting both in excitation and ionization of the atoms of the medium itself

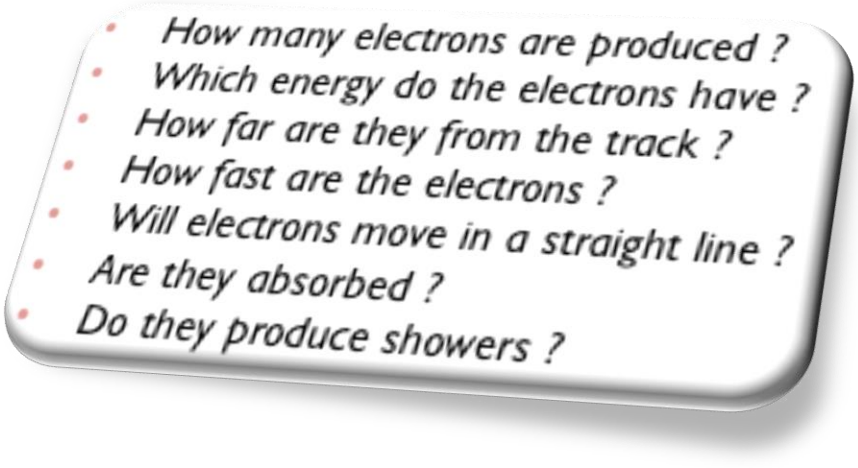
Ionization

Any charged particle traversing a gas will loose energy due to interactions with the atoms of the gas. This results in:

- **Excitation**, the particle passes a specific amount of energy to a gas atom
- **Ionization,** the particle knocks an electron off the gas atom, and leaves a positively charged ion

Resulting primary e^- will have enough kinetic energy to ionize other atoms of ga **onization**

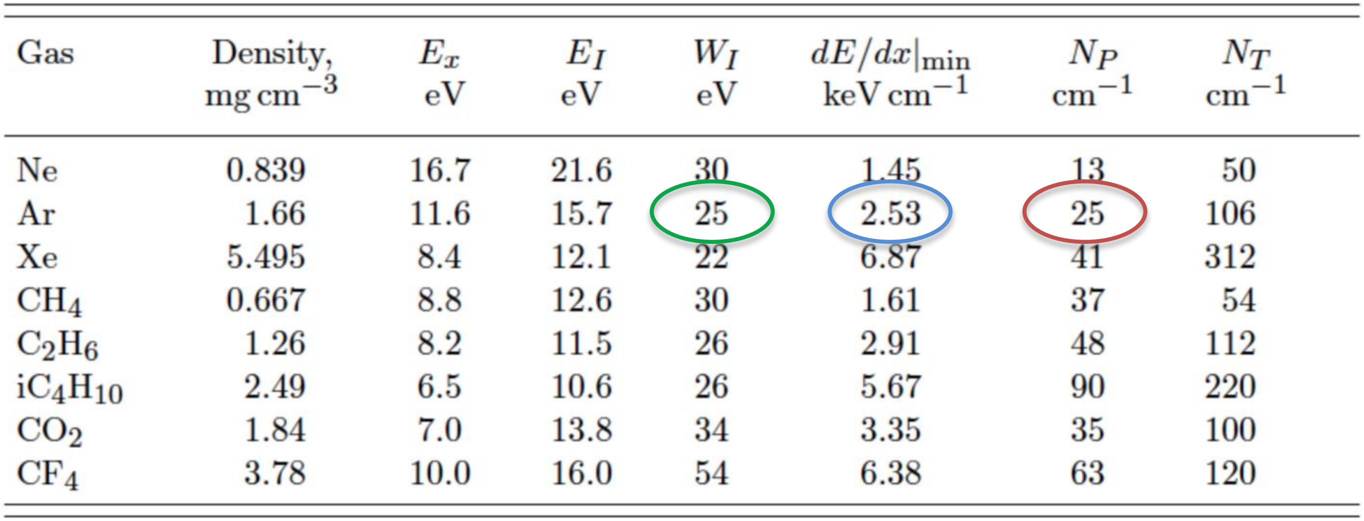




- How many electrons are produced ?
- Which energy do the electrons have ?
- How far are they from the track ?
- How fast are the electrons ?
- Will electrons move in a straight line ?
- Are they absorbed ?
- Do they produce showers ?

• Ionization •

Energy Loss of Charged Particles in Gases



Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{\min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

n_p = 25 ion pairs/cm

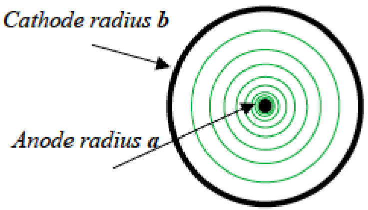
$n_T = \Delta E/W_i$ = 2.5 keV/cm / 25 eV = 100 ion pairs/cm

$n_p / n_T = 4$

Amplification

- The average distance between primary interactions is around 200-300 μm, and each primary produces few secondaries on average
- 100 pairs are not easy to detect, typical noise of an amplifier is ~1000 e^-
- **Need to MULTIPLY the electrons**
- Multiplication requires fields where the e^- energy occasionally is sufficient to ionise

THIN ANODE WIRE

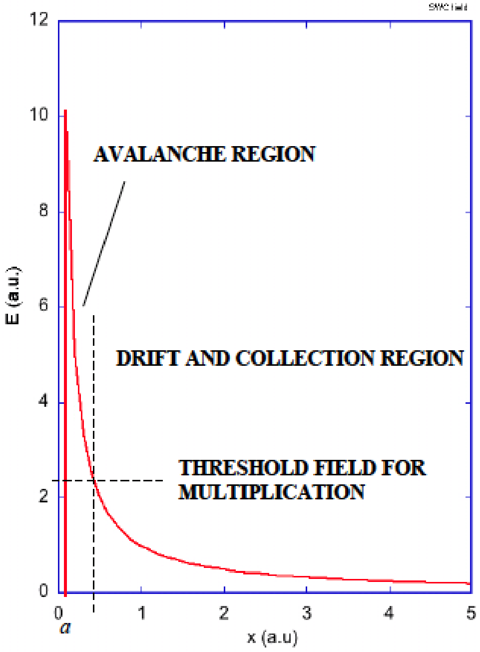


ELECTRIC FIELD AND POTENTIAL:

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

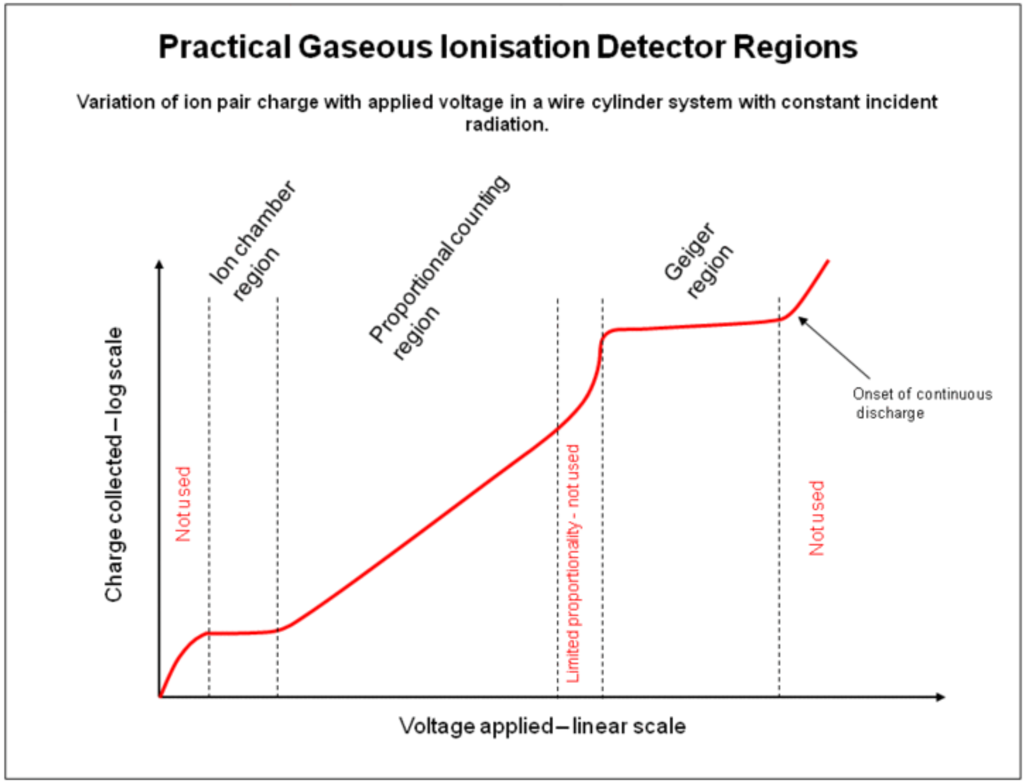
$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length



Gaseous Det. Regions

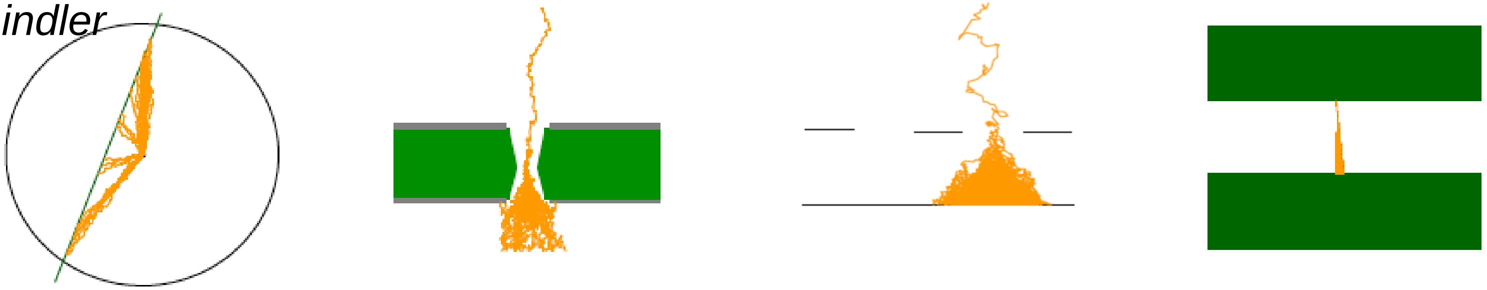
The different regions :

- Recombination before collection
- Ionisation chamber; collect all primary charge. Flat area.
- Proportional counter (gain to 10^6); secondary avalanches need to be quenched.
- Limited proportionality (secondary avalanches distorts field, more quenching needed).
- Geiger Muller mode, avalanches all over wire, strong photoemission, breakdown avoided by cutting HV.



Principle

- A charged particle **ionizes** gas atoms/molecules along its track; neutral particles do it via conversion processes,
- An electric field **transports** electrons and ions towards electrodes,
- Electrons are **multiplied** in a strong electric field,
- The **motion** of electrons and ions induces a current on the readout electrodes
- Signals are processed and recorded



Ref. H. Schindler

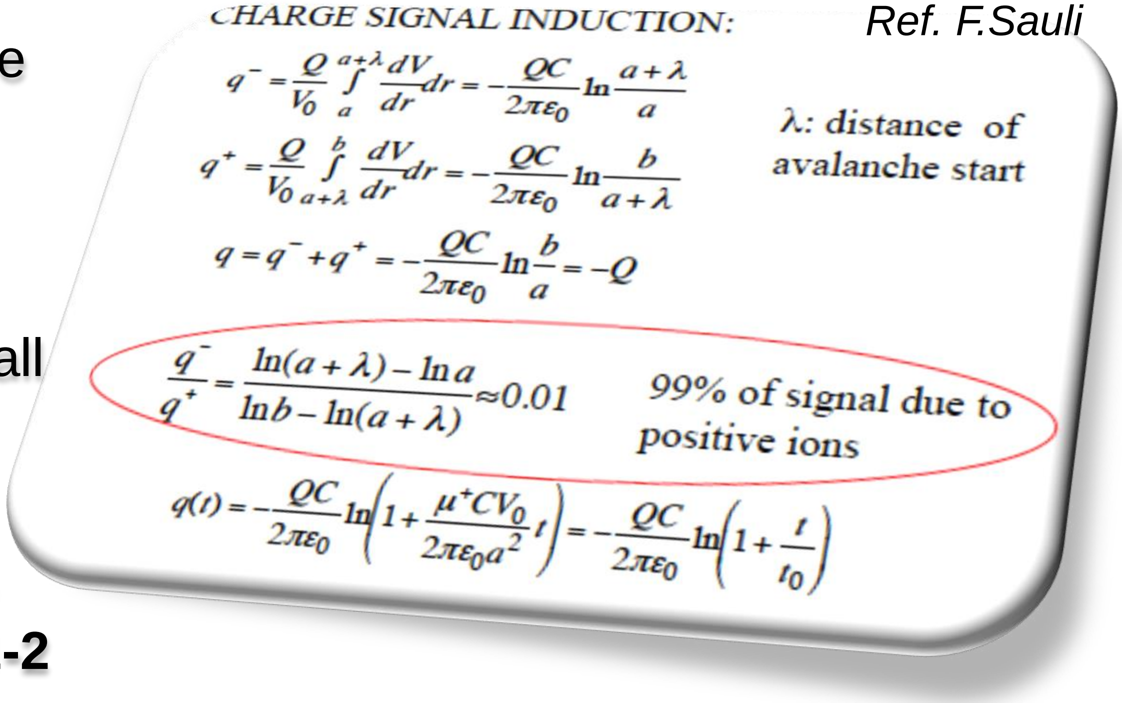
• Signal •

Electron avalanche occurs very close to the wire, with first multiplication occurring ~2x the wire radius.

Electrons move to the wire surface very quickly (<<1ns), but the ions drift to the tube wall more slowly (~100 μs).

Total charge induced by the electrons amount to only ~1-2 % of the total charge.

Ref. F.Sauli



CHARGE SIGNAL INDUCTION:

$$q^- = \frac{Q}{V_0}\int_a^{a+\lambda}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{a+\lambda}{a}$$

$$q^+ = \frac{Q}{V_0}\int_{a+\lambda}^{b}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a+\lambda}$$

λ: distance of avalanche start

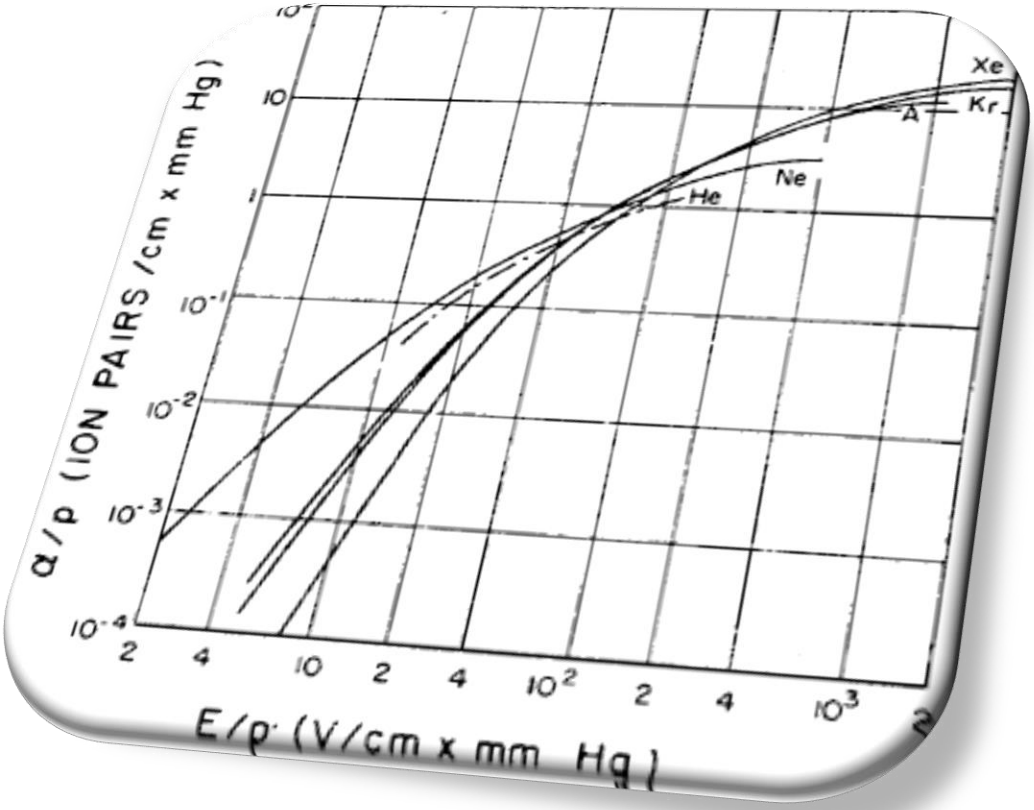
$$q = q^- + q^+ = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a} = -Q$$

$$\frac{q^-}{q^+} = \frac{\ln(a+\lambda)-\ln a}{\ln b-\ln(a+\lambda)} \approx 0.01$$

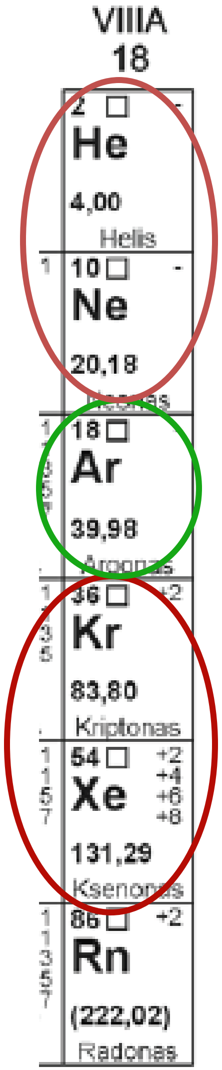
99% of signal due to positive ions

$$q(t) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{\mu^+ C V_0}{2\pi\varepsilon_0 a^2}t\right) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1+\frac{t}{t_0}\right)$$

Noble Gases



Noble gases require the lowest electric field for formation of avalanche

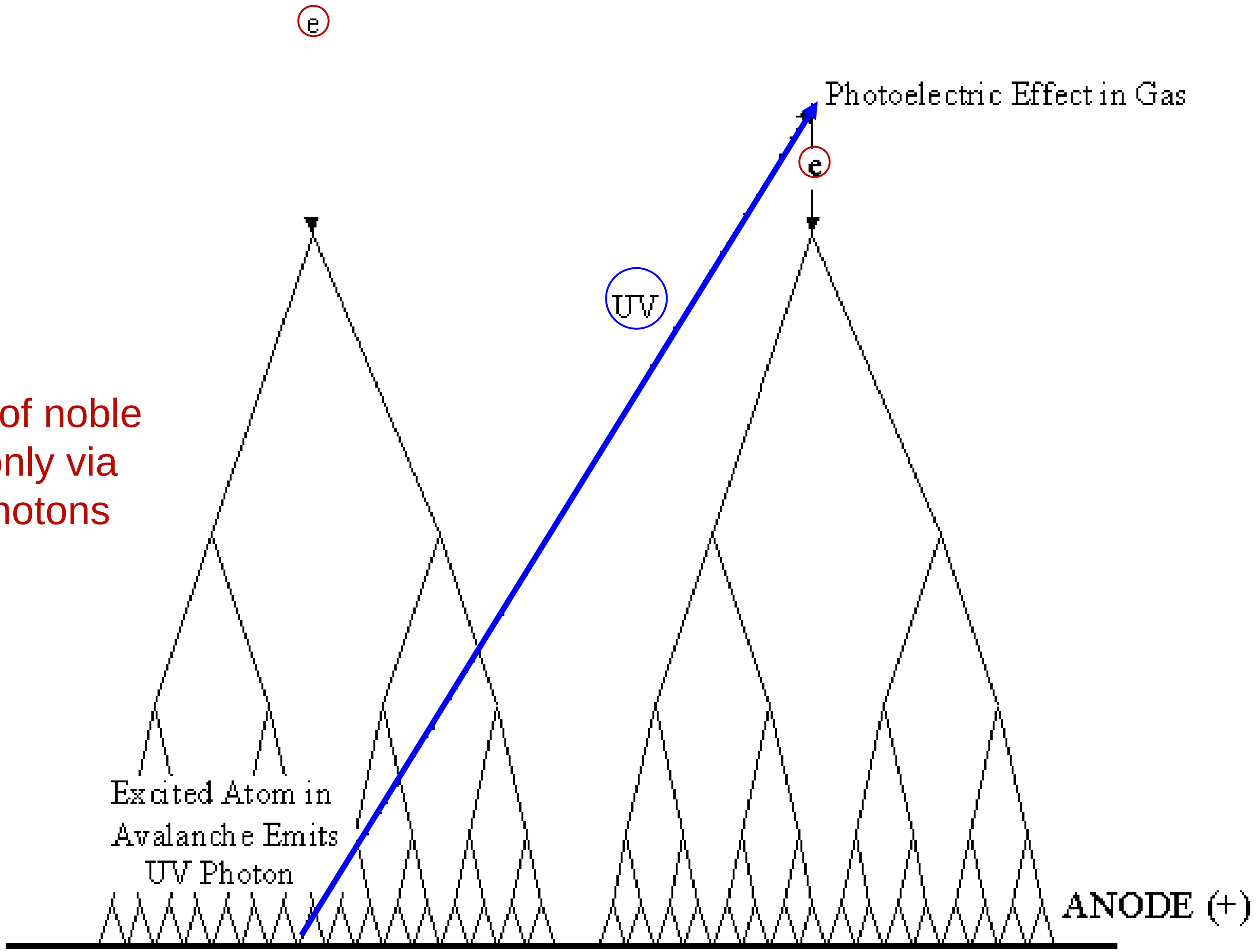


Light

Abundant
Inert
Cheap

Expensive

De-excitation of noble gases occur only via emission of photons

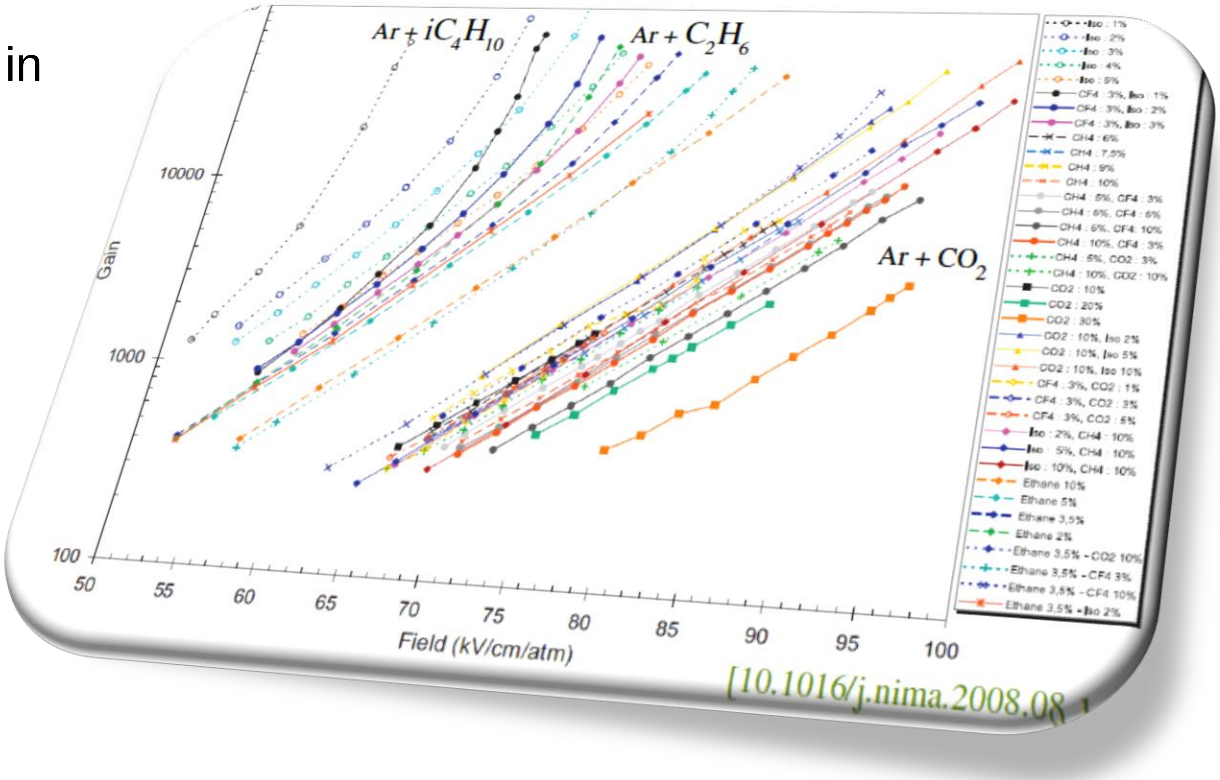


Primary avalanche **Secondary avalanche**

Quencher Gases

A polyatomic gas acts as a QUENCHER, i.e., absorbs photons in a large energy range due to the large amount of non-radiative excited states (rotational and vibrational)

- Most organic compounds in the HC and -OH families. The quenching efficiency increases with the nb of atoms in the molecule
- Freons, BF_3
- CO_2: non flammable, non polymerizing, easily available



[10.1016/j.nima.2008.08

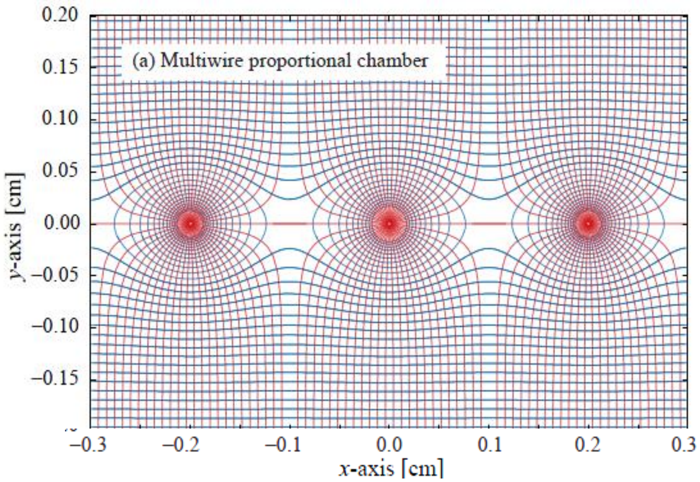
• Gas in LHC detectors •

Experiment	**Sub- Detector**	**Gas Mixture**
ALICE	TPC, TRD, PMD	Noble Gas **+ CO_2**
ATLAS	CSC, MDT, TRT	
CMS	DT	
LHCb	OT straws	
TOTEM	GEM, CSC	
LHCb	MWPC, GEM	Ar **– CO_2 - CF_4**
CMS	CSC	
ATLAS, CMS, ALICE	RPC	$C_2H_2F_4$ - iC_4H_{10} - SF_6
ATLAS	TGC	CO_2 – n-pentane
LHCb	RICH	CF_4 or C_4F_{10}

• MWPC •

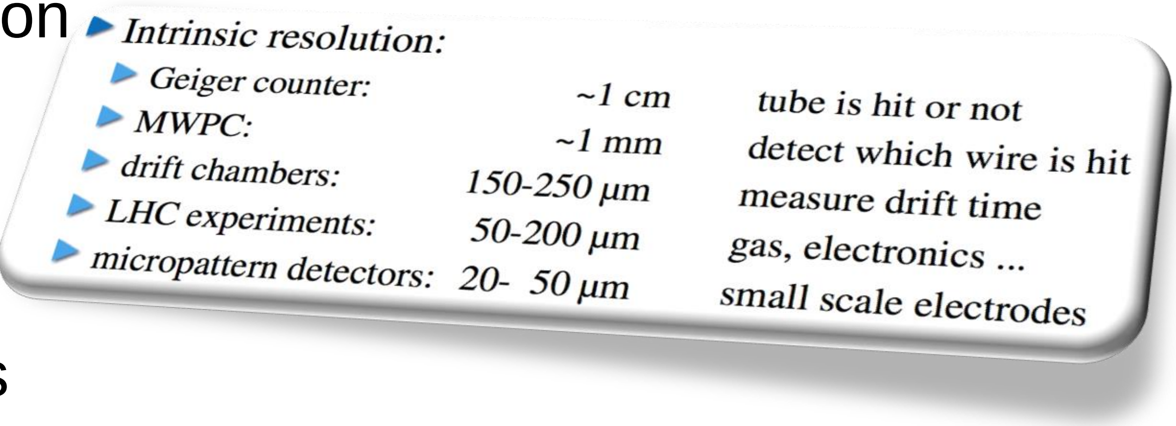
Noble Prize in 1992

- Fast position-sensitive detectors (1968)
- Continuously active
- Efficient at particle fluxes up to several MHz/cm2
- Sub-mm position accuracy
- **First electronic device allowing high statistics experiments !!**



Gas Detectors

- Good spatial resolution
- Good dE/dx
- Good Rate capability
- Fast & Large Signals
- Low radiation length
- Large area coverage
- Multiple configurations/flexible geometry

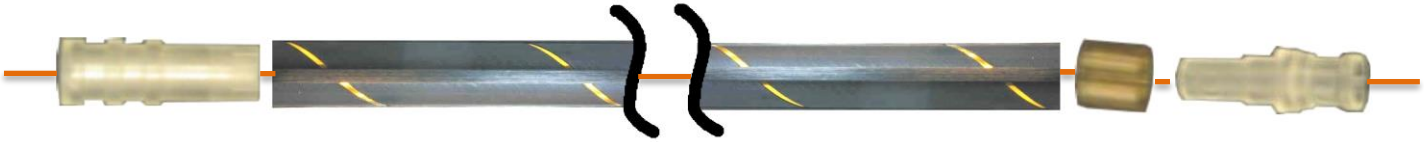


- *Intrinsic resolution:*

Geiger counter:	~1 cm	tube is hit or not
MWPC:	~1 mm	detect which wire is hit
drift chambers:	150-250 μm	measure drift time
LHC experiments:	50-200 μm	gas, electronics ...
micropattern detectors:	20- 50 μm	small scale electrodes

Transition Radiation Tracker

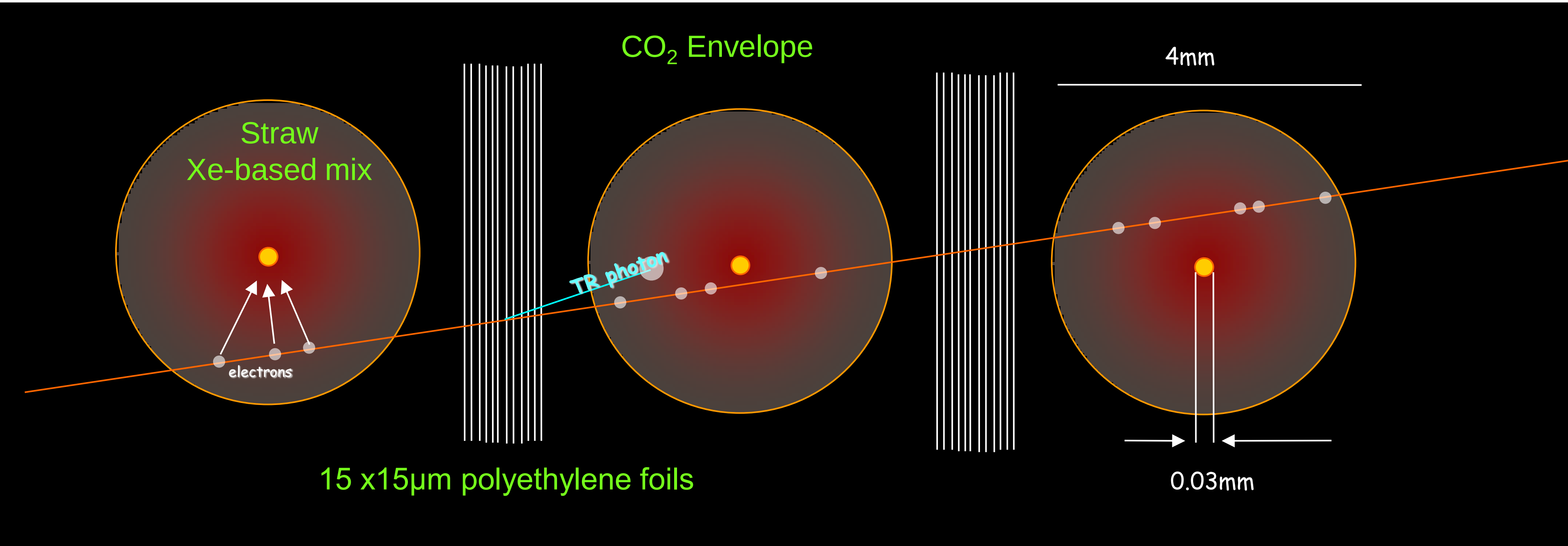
- TRT is an array of 350 000 small diameter drift tubes
- Volume 12 m^3
- Basic detector element: **straw tube with 4mm diameter with a 0.03 mm diameter gold-plated tungsten wire in the center**



- 50 000 straws in Barrel, each straw 144 cm long, ends of straws are read out separately
- 250 000 straws in both endcaps, each straw 39 cm long
- **Continuous tracking: on average 30 two-dimensional space points with ~130-160 µm resolution for charged particle tracks**
- Transition radiation: TRT provides additional **information on the particle type** that flew through the detector, i.e. if it is an electron or pion

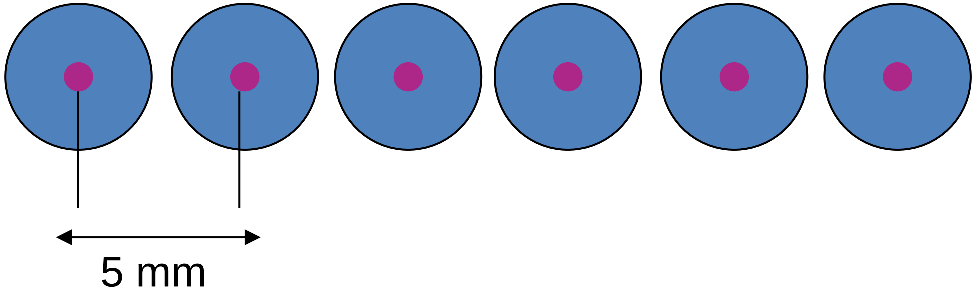
Transition Radiation

- TRT provides **particle identification** through the detection of transition radiation X-ray photons
- TR: **photon emitted** by a charged particle when traversing the boundary between materials with different dielectric constants
- **Electron identification makes use of the large energy depositions due to TR**. Typical TR photon energy depositions in the TRT are 8–10 keV, while minimum-ionizing particles, such as pions, deposit ~2 keV. The parameter used in electron identification is the number of local energy depositions on the track above a given threshold.

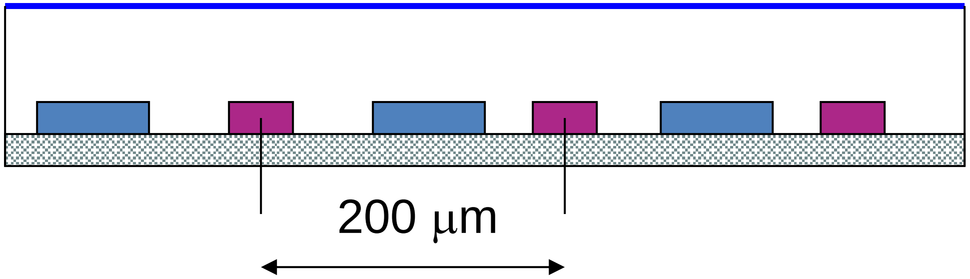


TRT

Increasing Cell Granularity



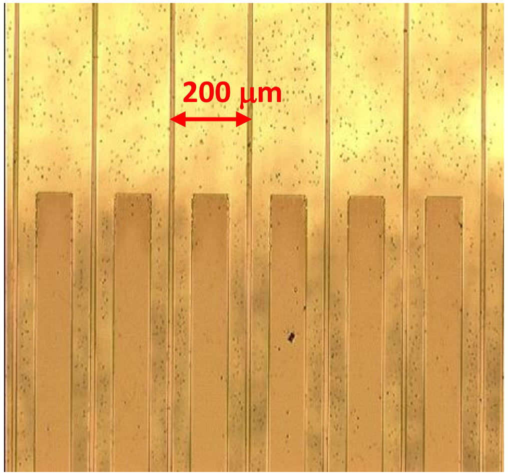
STRAW TUBES
Anode-cathode distance: 2 mm
Spatial resolution ~ 130-300 µm

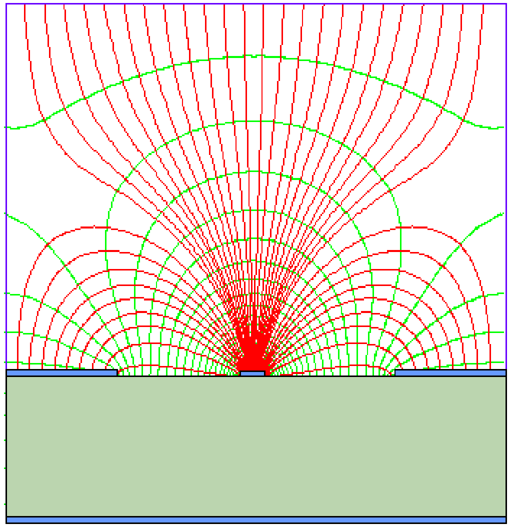


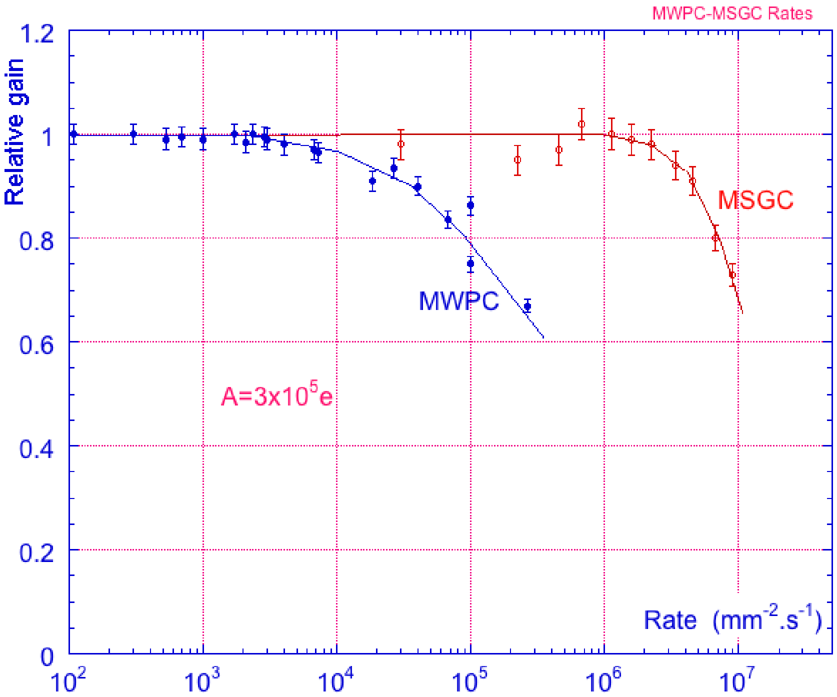
MICRO STRIP GAS CHAMBERS (MSGC - A.Oed,1988)
Semiconductor industry technologies
Anode-cathode distance: 40 µm
Spatial resolution ~ 40 µm

• MSGC •

Ref. R.Bouclier et al.
Nucl. Instr. and Meth. A323(1992)



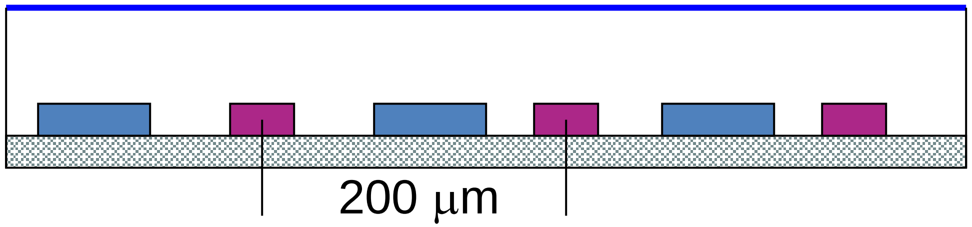




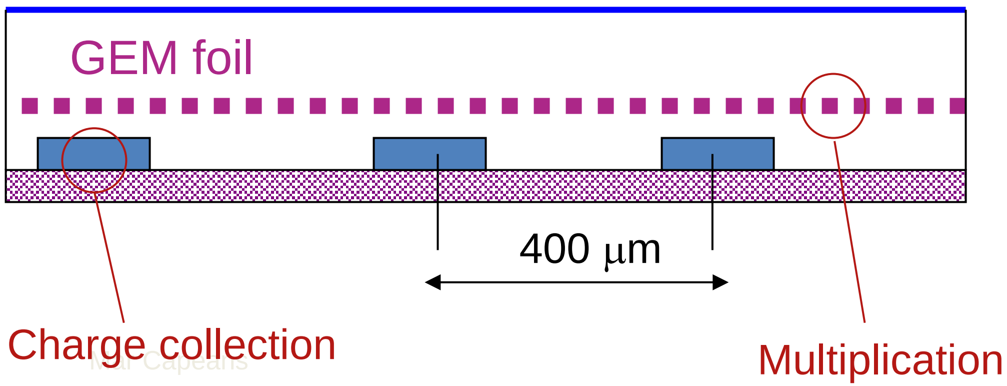
MWPC… Rate capability limited by space charge defined by the time of evacuation of positive ions

MSGC… Very high rate capability due to small pitch and fast ion collection

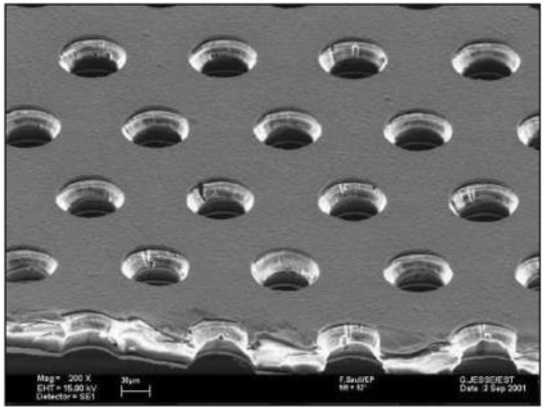
Decoupling Multiplication from Charge Collection



Micro Strip Gas Chamber



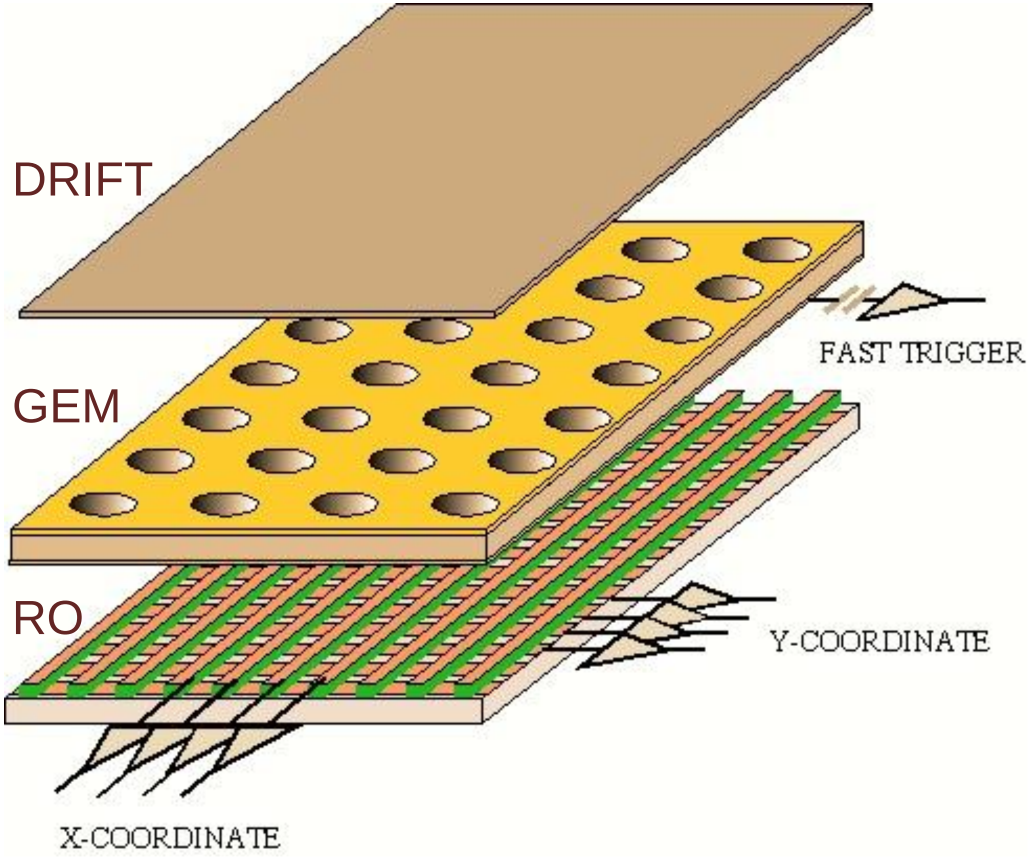
Gas Electron Multiplier
(GEM – F.Sauli, 1998)
Spatial resolution ~ 50 µm
Time resolution better than 10 ns



Thin metal-coated polymer foils
70 µm holes at 140 mm pitch

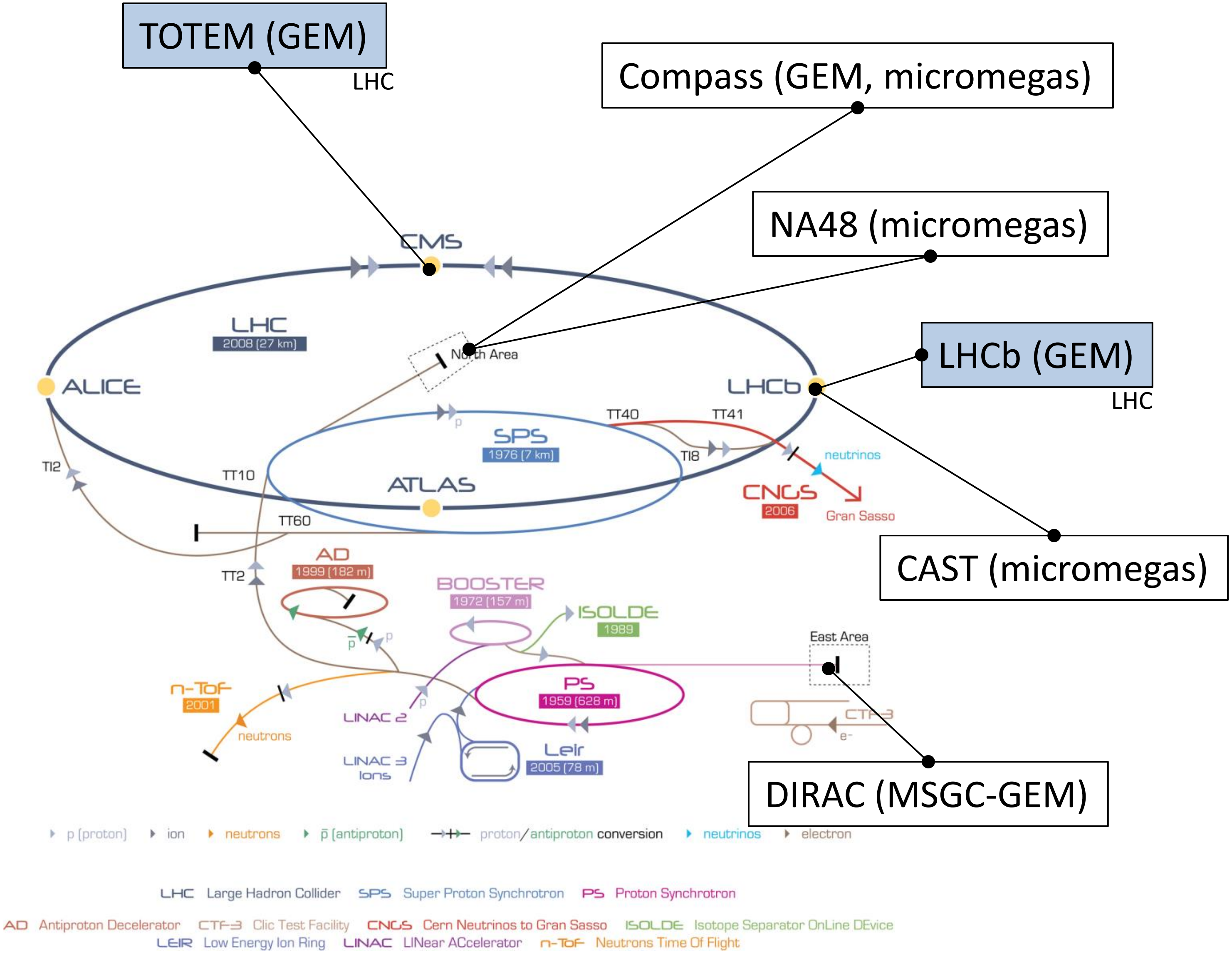
GEM Detectors

- Primary electrons are released by ionizing radiation in the gas (E-field between drift plane and GEM)
- By applying a suitable voltage difference between the two metal sides of the GEM, an electric field with an intensity as high as 100kV/cm is created inside the holes which act as multiplication channels
- Readout electrodes are at ground potential; electron charge is collected on strips or pads, ions are partially collected in the bottom of the GEM foil



MPGD detectors already running at CERN….

Slide: E.Oliveri, CERN



TOTEM (GEM)

LHC

Compass (GEM, micromegas)

NA48 (micromegas)

LHCb (GEM)

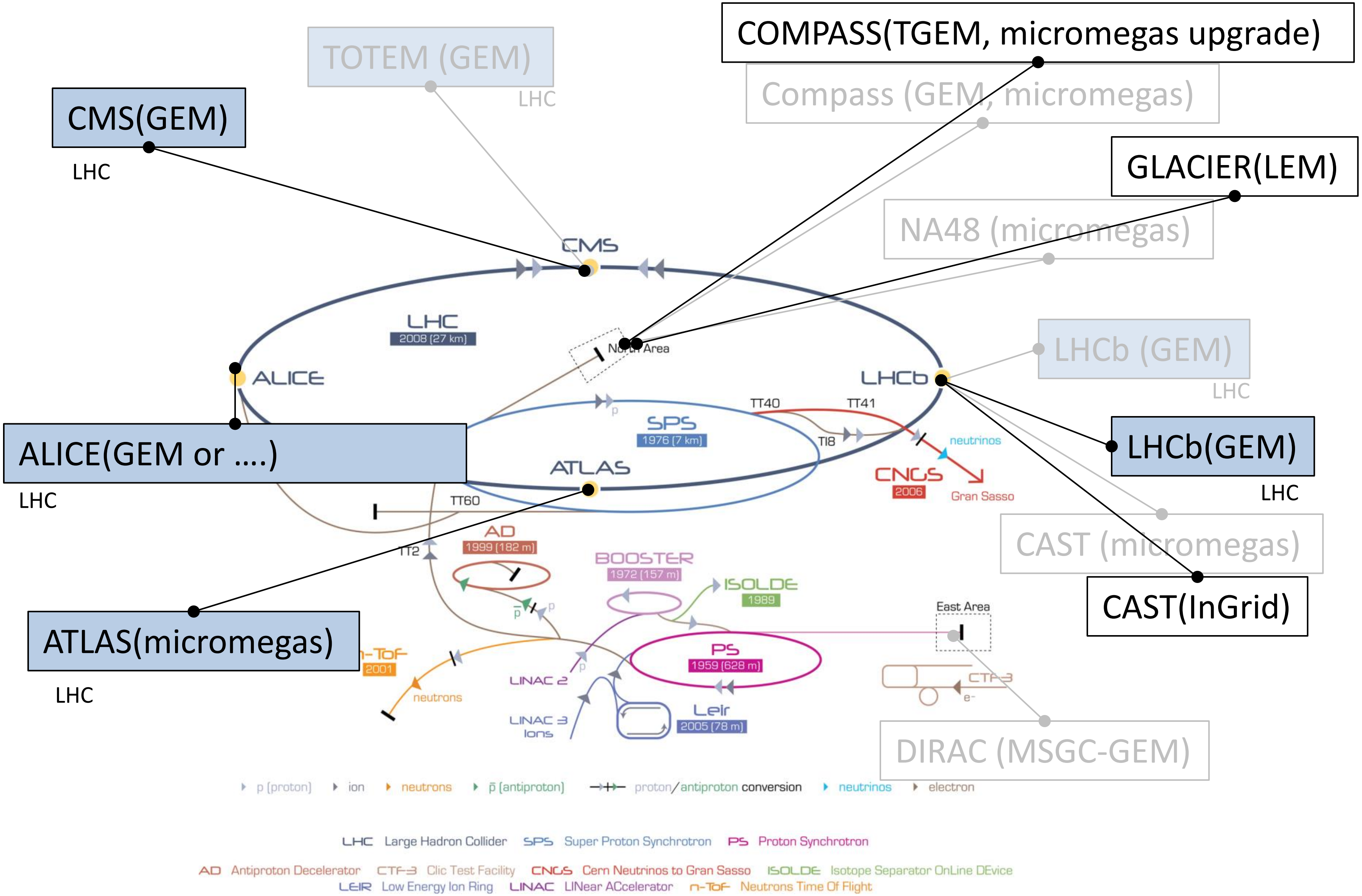
LHC

CAST (micromegas)

DIRAC (MSGC-GEM)

Slide: E.Oliveri, CERN

…. and possible upgrades



TOTEM (GEM)
LHC

CMS(GEM)
LHC

COMPASS(TGEM, micromegas upgrade)

Compass (GEM, micromegas)

GLACIER(LEM)

NA48 (micromegas)

LHCb (GEM)
LHC

ALICE(GEM or ….)
LHC

LHCb(GEM)
LHC

CAST (micromegas)

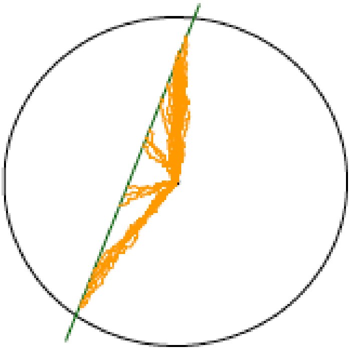
CAST(InGrid)

ATLAS(micromegas)
LHC

DIRAC (MSGC-GEM)

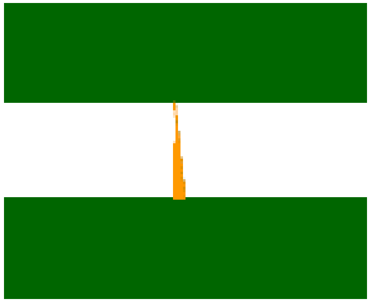
… and other proposals in progress for future upgrades

• Time Resolution •



Cylindrical geometries have an important limitation: Primary electrons have to drift close to the wire before the charge multiplication starts

Limit in the time resolution ~ 0.1μs

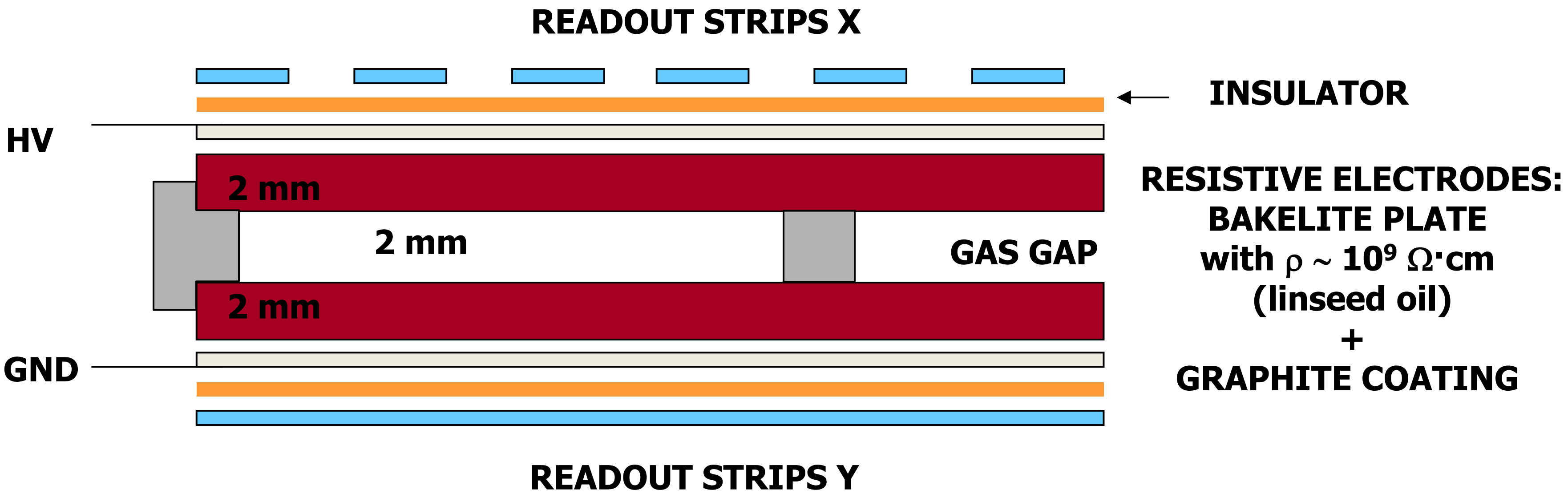


In a parallel plate geometry the charge multiplication starts immediately because all the gas volume is active (uniform and very intense field). This results in much better time resolution (~ 1 ns)

• RPC •

Developed in the 80s as an **affordable, robust, large area detector** with:

Fast timing: < 1 ns to ps for MRPC
Space resolution: ~mm
Rate capability: up to ~100 Hz/cm^2



• Developments for LHC RPCs •

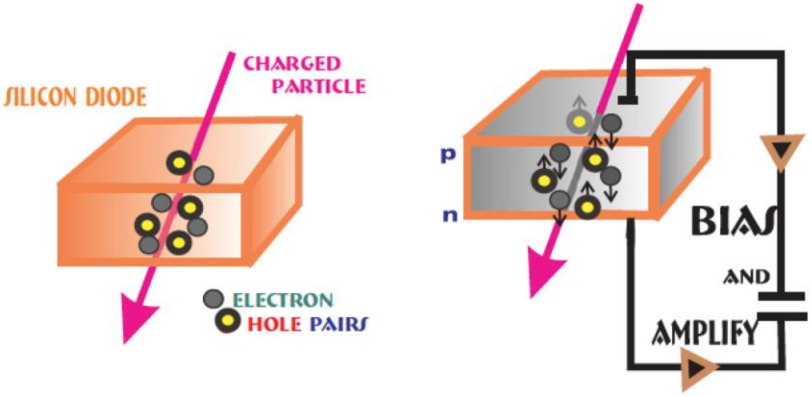
- Large Area Coverage (> 5000 m^2)
  - Industrialization of assembly (cheap, large areas, custom geometries…)
- Increased Rate Capability (~kHz/cm^2)
  - Mode of operation
  - Volume resistivity of electrodes
  - And gas gap, electrode thickness, FE…
- Handling Large and Expensive Gas Volume
- Large Background Radiation (50 mC/cm^2 ALICE and CMS 500 mC/cm^2 ATLAS)
- Stability for long period (> 10 y)

Semiconductors

- Used in nuclear physics for Energy measurements since the 50ies
- Appear in HEP in the 70ies
- In the 80ies, planar technique of producing silicon radiation sensors, permitting segmentation of one side of the junction and the use of signals recorded on the segments to determine particle positions

- Solid state ionization chamber, member of the large family of ionization detectors. A Si detector takes advantage of the special electronic structure of a semi-conductor

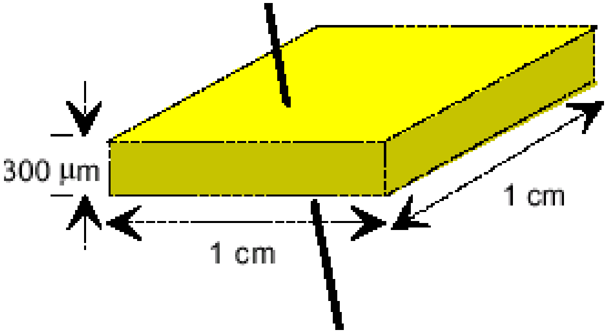
When a charged particle traverses Si, it produces ionizing and non-ionizing E Loss. The latter produces radiation damage, while ionization loss causes the creation of e-hole pairs which produce the signal.
The of pair depends on the amount of ionization, thus on the charge and momentum of the incoming particle and thickness of material.



• Semiconductors •

- **Very attractive in HEP because of:**
  - Good intrinsic energy resolution
    - Si: 1 e-hole pair for every 3.6 eV released by a crossing particle
    - Gas: 30 eV required to ionize a gas molecule
    - High primary ionization (larger signal), no amplification
  - Si High density reduces the range of secondary e, thus good spatial resolution
  - The granularity can also be very high
  - Thin, therefore can be positioned close to the interaction point
  - E loss: typical detector thickness (300 μm) result in 3.2 x10^4 e-/hole pairs
  - Industrial process (high yield, continuous development…)

Semiconductors



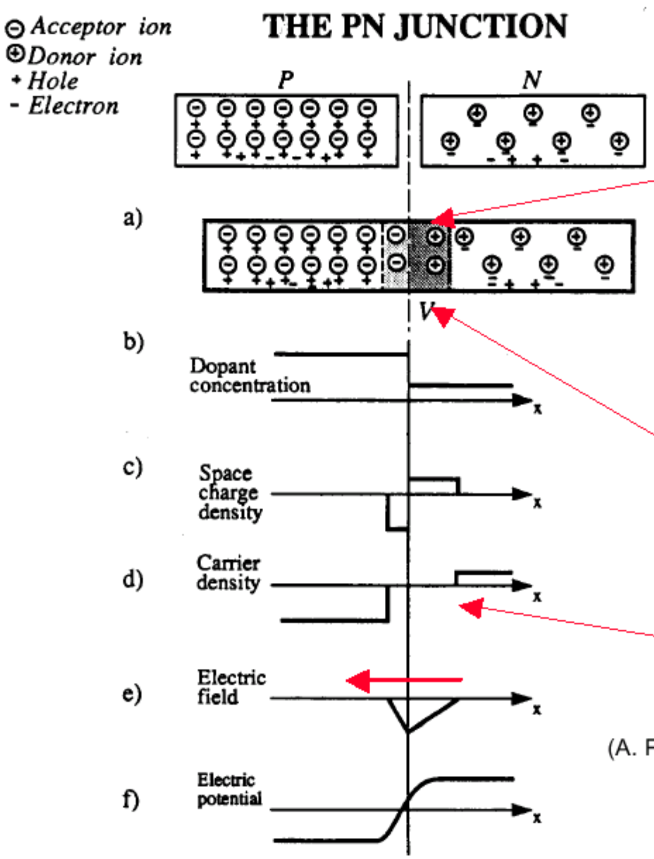
Current conduction in a semiconductor occurs through the movement of free electrons and "holes", collectively known as charge carriers. Adding impurity atoms to a semiconducting material, known as "doping", greatly increases the number of charge carriers within it. When a doped semiconductor contains mostly free holes it is called "p-type", and when it contains mostly free electrons it is a "n-type". Semiconductor materials used in electronic devices are doped under precise conditions to control the location and concentration of p- and n-type dopants. A single semiconductor crystal can have many p- and n-type regions; the p–n junctions between these regions are responsible for the useful electronic behaviour.

- Intrinsic silicon will have electron density = hole density; 1.45×10^{10} cm^{-3} (from basic semiconductor theory)

- In the volume above this would correspond to 4.5×10^{8} free charge carriers; compared to around 3.2×10^{4} produces by MIP (Bethe Bloch loss in 300 um Si divided by 3.6 eV)

- Need to decrease number of free carriers; use depletion zone (reduce temperature would also help but one would need to go to cryogenic temperatures)

• Semiconductors •



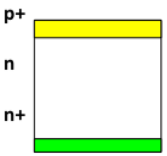
diffusion of e^- into p-zone, h^+ into n-zone → potential difference stopping diffusion

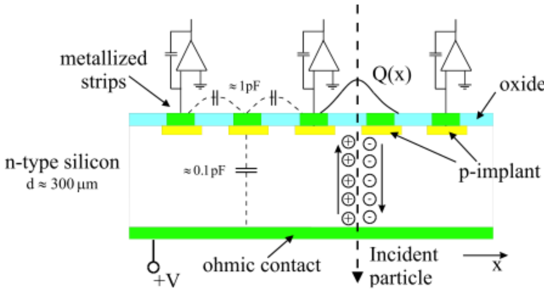
thin depletion zone

no free charge carriers in depletion zone

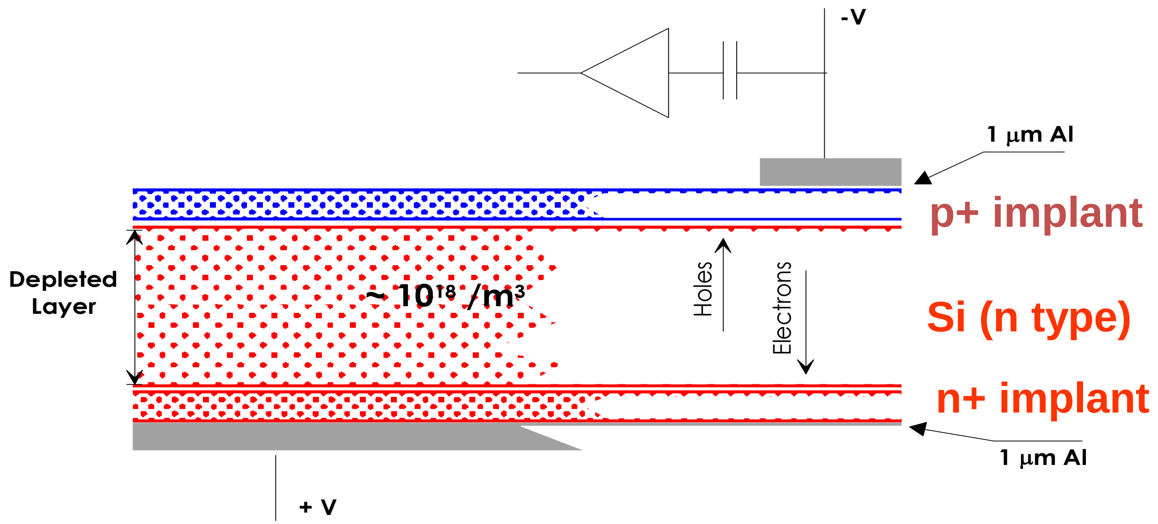
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

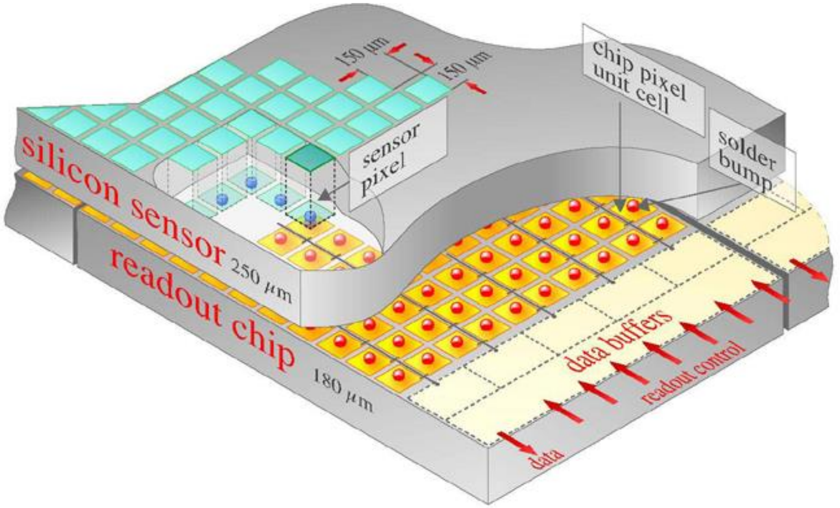
Semiconductor detectors are basically p^+- n diodes made on high resistivity silicon

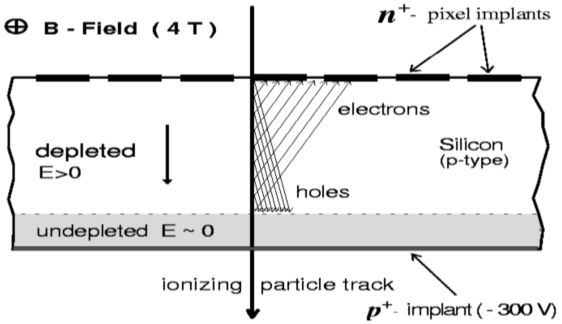




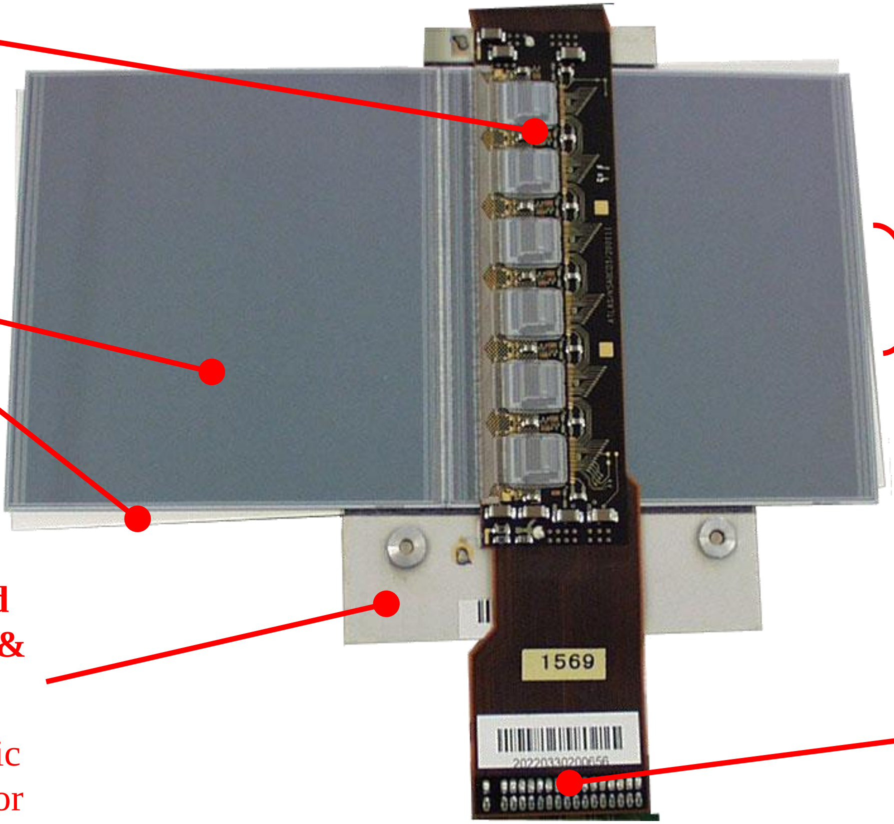
Semiconductors







ATLAS, Barrel SCT module



Hybrid assembly

with readout chips

12.8 cm

6 binary readout chips on either sensor side; sig:noise = 14:1

4 Silicon sensors

280 µm thick

2.3° stereo angle

Overlap in ϕ & z to adjacent modules

768 p^+ microstrips Cell size: 80 µm [ϕ pitch] × 13 cm [z]

Overall 6.3 10^6 channels

Be module baseboard with mounting points & central TPG

TPG (thermal pyrolythic graphite) plate for sensor cooling

Connector

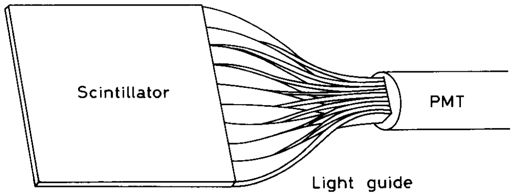
Power & data

Fully equipped double sided electrical module with baseboard and readout hybrids

• Scintillators •

- Scintillators are materials that produce sparks or scintillations of light when ionizing radiation passes through them. The charged particle excites atoms in the scintillator, e- returns to ground state by emitting a photon

- Different types of scintillators
  - Inorganic crystalline scintillators (NaI, CsI, BaF$_2$..)
  - Nobel Gas (Ar)
  - Organic (Liquids or plastic scintillators)



Large plates of scintillators Coupled to single PMT

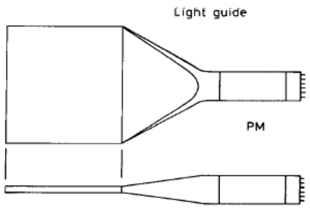
- Many different geometries

- The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way.

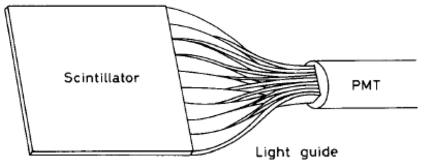
Scintillators

External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov light. See examples.

- Light guides: transfer by total internal reflection (+outer reflector)

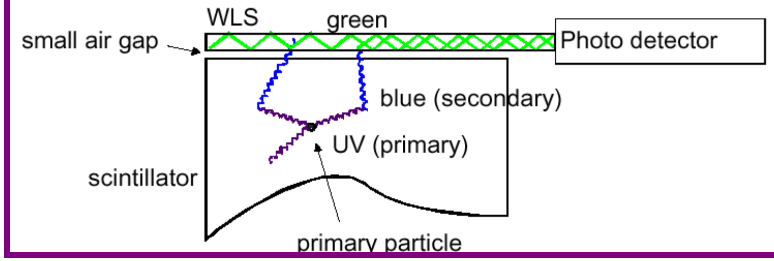


"fish tail"



adiabatic

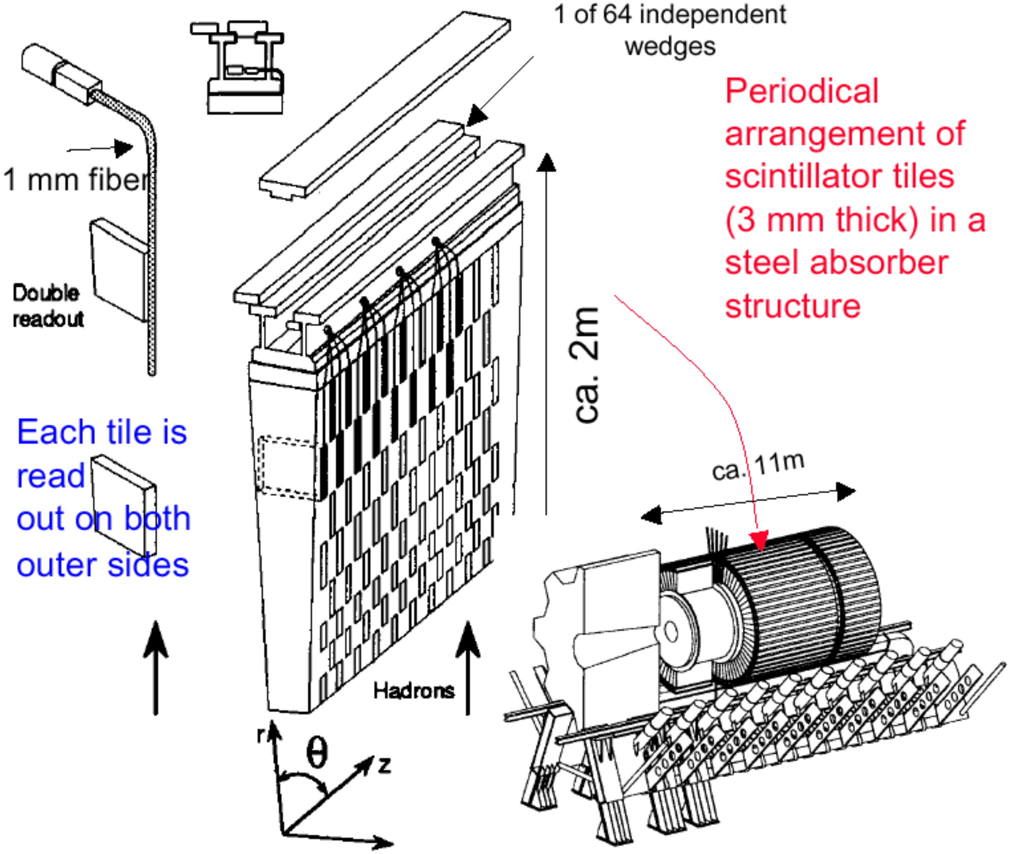
- wavelength shifter (WLS) bars



ATLAS Hadron Calorimeter:

(ATLAS TDR)

Scintillating tile readout via fibers and photomultipliers



1 of 64 independent wedges

Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure

Each tile is read out on both outer sides

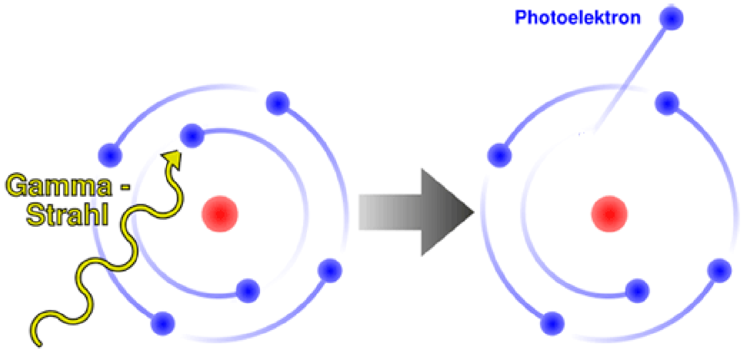
From C.Joram

• Photo-detectors •

Slide: C.Joram, CERN

Purpose: Convert light into detectable electronic signal

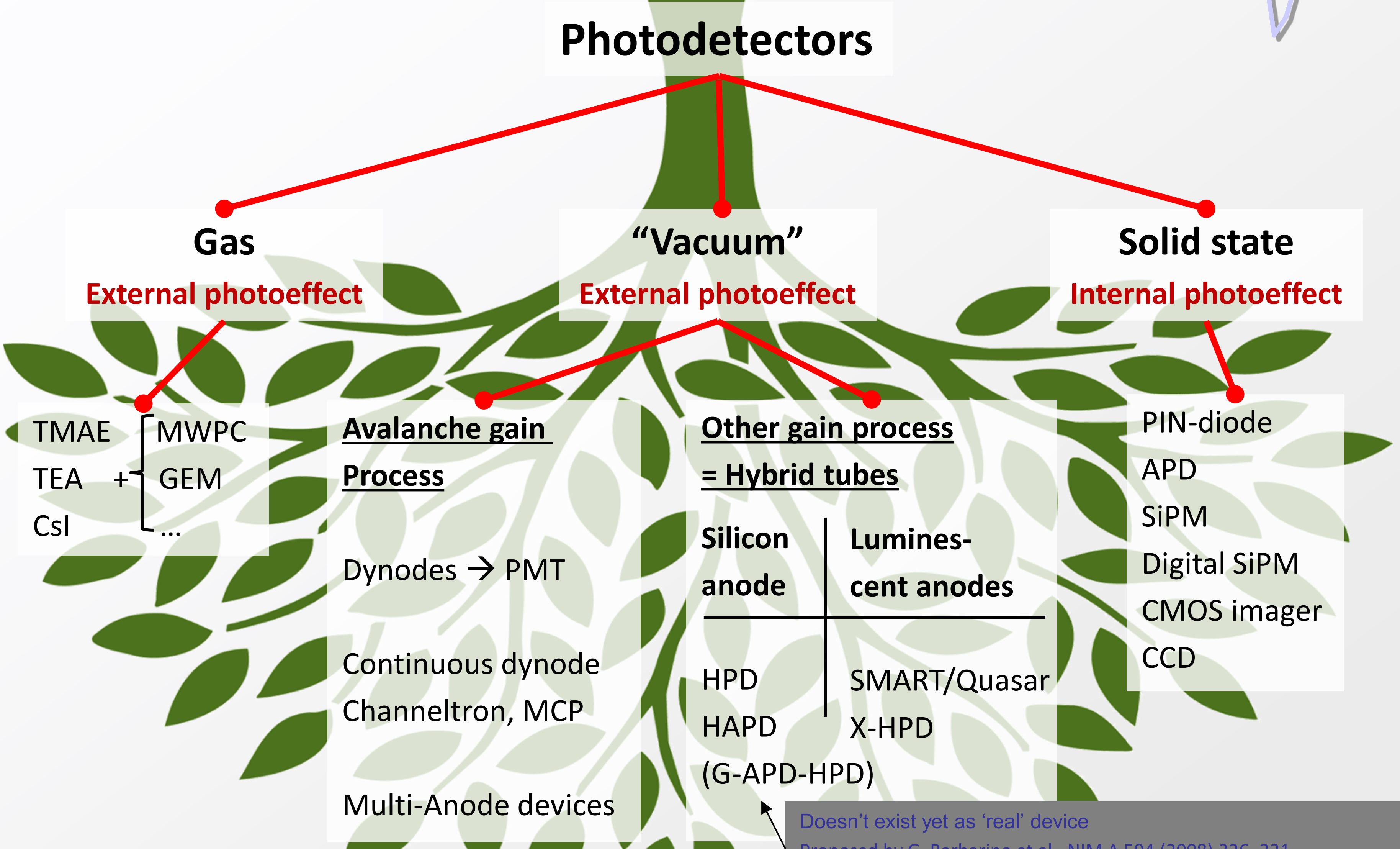
Principle: Use photoelectric effect to ‘convert’ photons (γ) to photoelectrons (pe)



Details depend on the type of the photosensitive material. Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

Photon detection involves often materials like K, Na, Rb, Cs (alkali metals) . They have the smallest electronegativity → highest tendency to release electrons.

Family tree of photo-detectors



Photodetectors

Gas

External photoeffect

TMAE, TEA, CsI + {MWPC, GEM, …}

"Vacuum"

External photoeffect

Avalanche gain Process

Dynodes → PMT

Continuous dynode

Channeltron, MCP

Multi-Anode devices

Other gain process = Hybrid tubes

Silicon anode	**Luminescent anodes**
HPD	SMART/Quasar
HAPD	X-HPD
(G-APD-HPD)	

Doesn't exist yet as 'real' device

Proposed by G. Barbarino et al., NIM A 594 (2008) 326–331

Proof of principle by CJ et al., NIM A 621 (2010) 171-176

Solid state

Internal photoeffect

- PIN-diode
- APD
- SiPM
- Digital SiPM
- CMOS imager
- CCD

• Calorimeters •

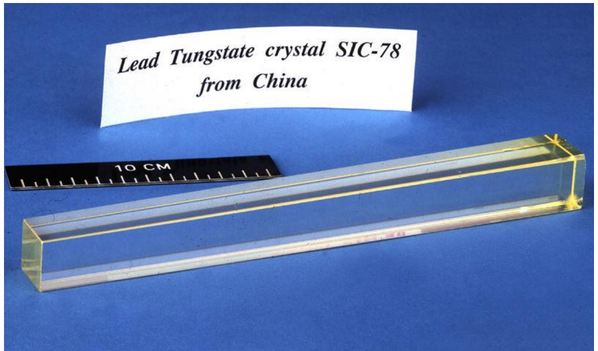
- Goal is to measure energy of incoming particle
  - **Detect E of neutral or charged particles**. Stop particles (absorb all the energía), except muon (heavy) & neutrinos (weak interaction).
  - Measure the integral of energy loss per depth
  - Sample the energy loss at several points

- Two types of calorimeters
  - Electromagnetic (photon and electron showers)
  - Hadron (pion, proton, neutron …)
- Two implementations
  - Homogeneous Calorimeter: absorber = active detector
  - Sampling Calorimeter: absorber is interleaved with active detector

• Calorimeters •

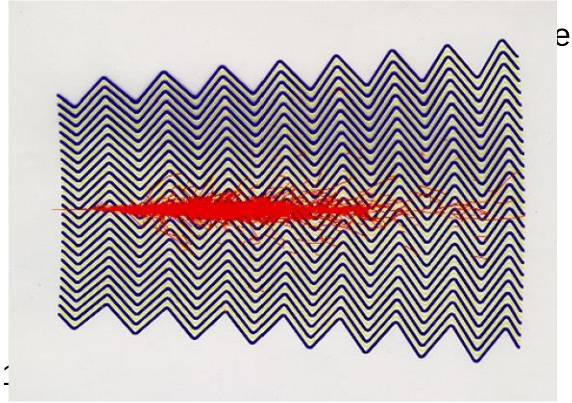
Homegeneous EM Calorimeter (CMS)

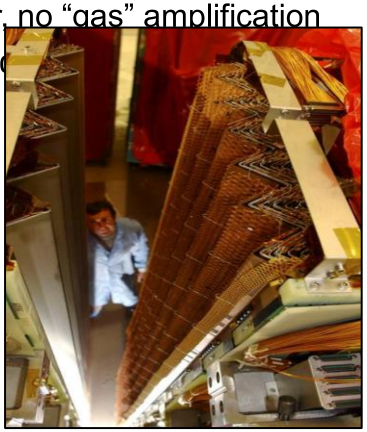
- Clear advantage: good energy resolution
  - the entire shower is kept in active detector material (no shower particle is lost in passive absorber)
- Disadvantages
  - limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)



Sampling EM Calorimeter (ATLAS)

- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible: gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)
- ATLAS is using LAr with “accordeon” shaped steel absorbers
  - LAr is ionized by charged shower particles
  - Charge collected on pads
    - ionization chamber, no “gas” amplification
    - ed





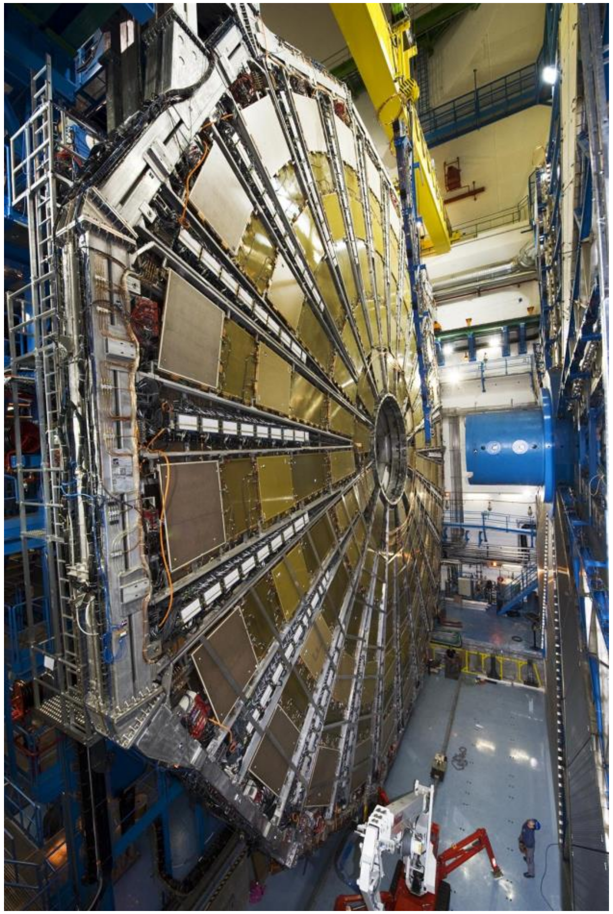
• Muon Systems •

- Function: muon detection; Muons are charged particles that are just like electrons and positrons, but 200 times heavier.

  Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by calorimeters. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal.

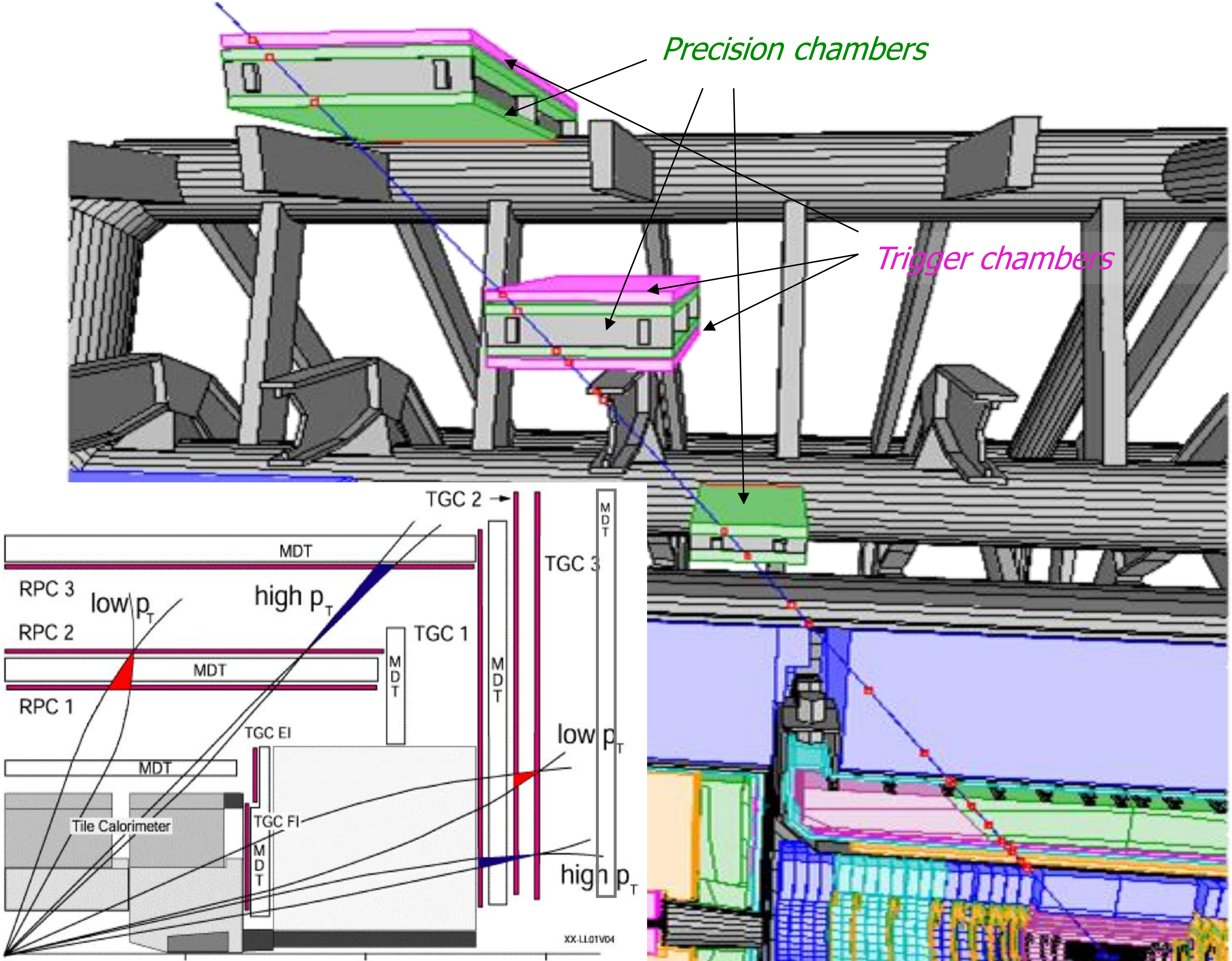
- Detection principle: Ionization detectors (gas), similar to precision trackers but usually of lower spatial resolution.

- They are fast detectors and are part of the Trigger system to select events



ATLAS,12 000 m^2, 1.1 Mchannels
Aligment precission <±30 mm

Muon Spectrometer

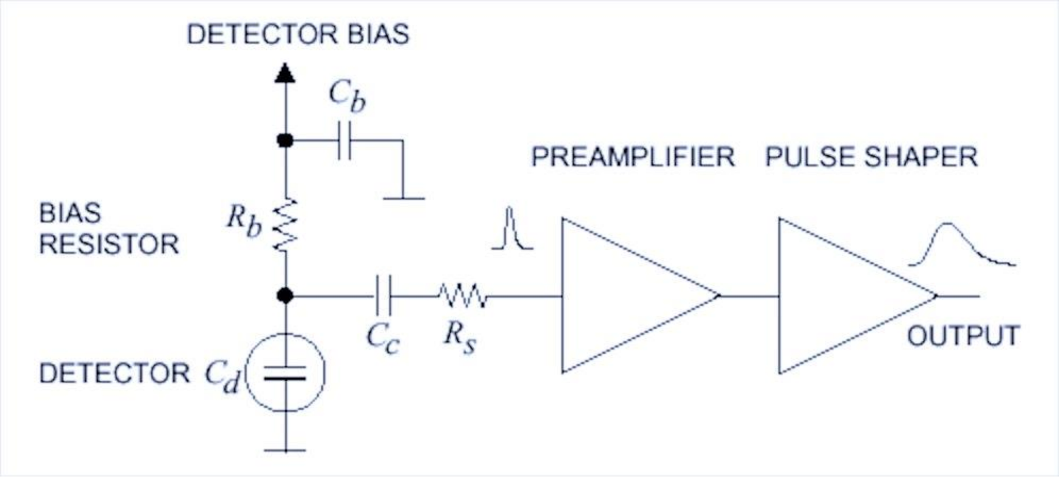


Precision chambers

Trigger chambers

Signals

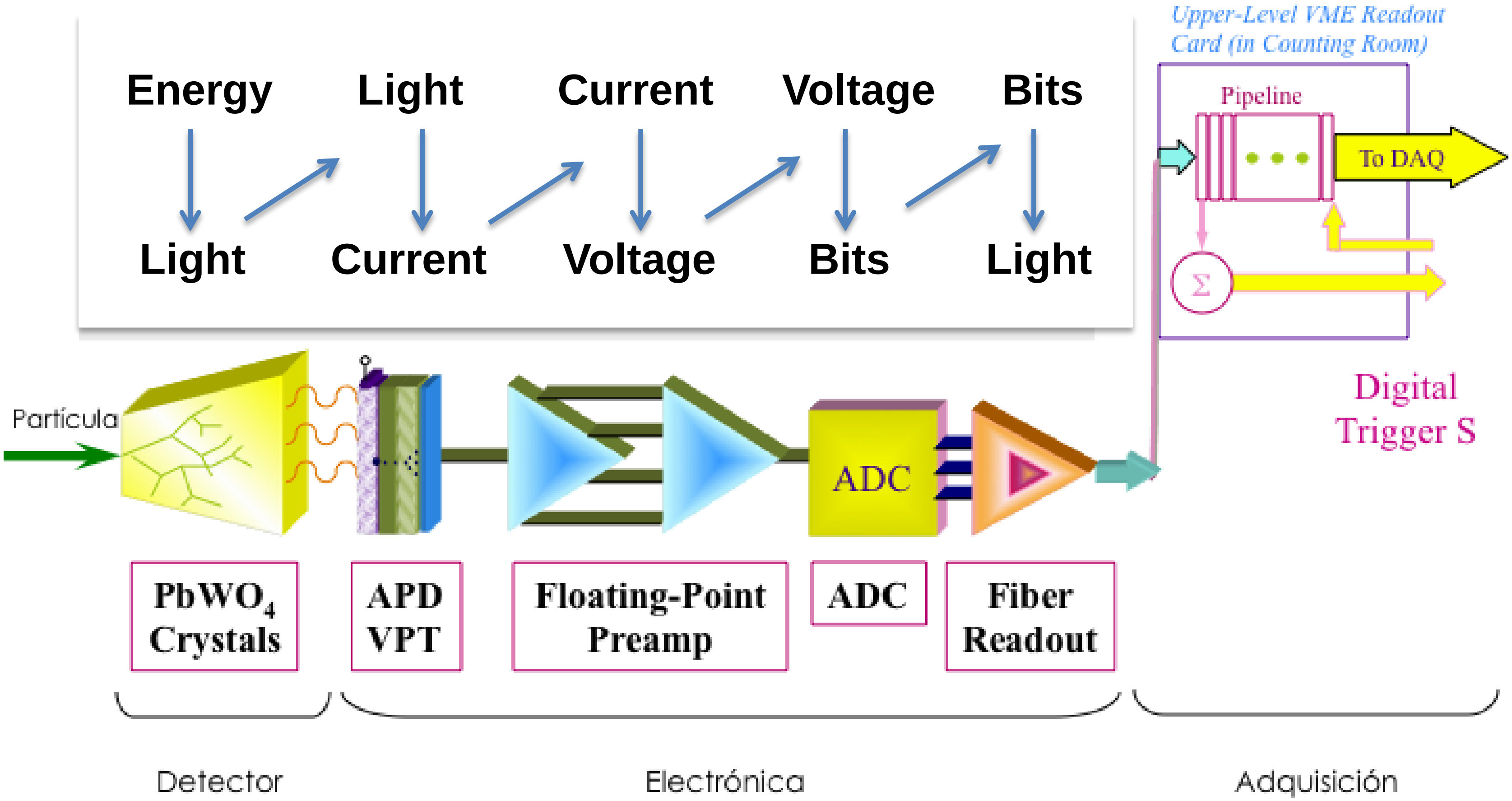
Most detectors rely critically on low noise electronics. A typical Front-End is shown below, where:



- Detector is represented by the capacitance C_d
- Bias voltage is applied through R_b
- Signal is coupled to the amplifier though a capacitance C_c
- R_s represents all the resistances in the input path

The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal.

Signals

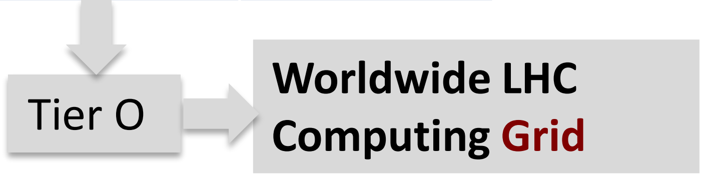


Energy → Light → Current → Voltage → Bits → Light

Data Acquisition, Storage, Distribution and Processing is as complex as the detector itself

- Large data production (~PB/sec) versus storage capability (~GB/sec) forces huge online selection
- 3 levels of triggers (first level fully electronics based)
- Data distribution for offline processing using GRID system

Trigger	Método	Entrada Sucesos/s	Salida Sucesos/s	Factor de reducción
Nivel 1	HW (⌠, Calo)	40 000 10^3	100 10^3	400
Nivel 2	SW (RoI, ID)	100 10^3	3 10^3	30
Nivel 3	SW	3 10^3	0.2 10^3	15


Tier O

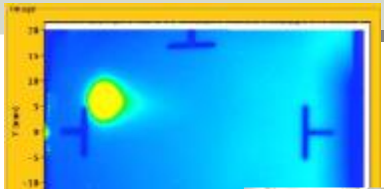
Worldwide LHC Computing Grid

HEP Detectors

Last generation of HEP detectors are incredibly complex and state of the art pieces of technology

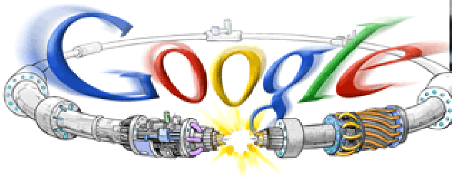
- Large use of (semiconductors/gas) radiation hard technology for trackers
- Calorimeters precise as never before
- Cryogenics detectors and magnet systems
- Detector systems have increased in size and complexity at least a factor 10
- The data flow and data processing is unprecedented
- Projects span over a lifetime of 3-4 decades, involving thousands of scientists

Experiment	Countries	Institutions	Scientists
ALICE	36	131	~1200
ATLAS	38	177	~ 3000
CMS	42	182	~ 3000
LHCb	16	65	~ 700



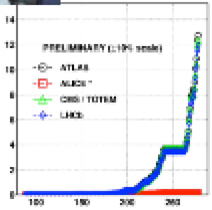
August 2008
First injection test

3.5 TeV



September 10, 2008
First beams around

November 29, 2009
Beam back



April 2010
Squeeze to
3.5 m

October 14 2010
1e32
248 bunches

fb^{-1}
1380
bunches

June 28 2011
1380 bunches

1380

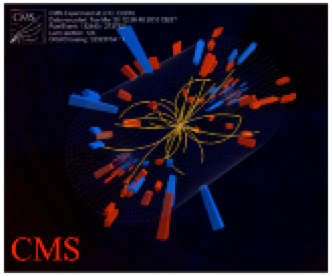
6 June, 2012
6.8e33

4 July, 2012
Higgs discovery

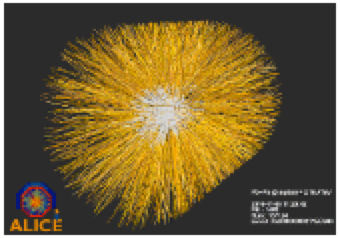
2008 | 2009 | 2010 | 2011 | 2012

September 19, 2008
Disaster
Accidental release of 600MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at

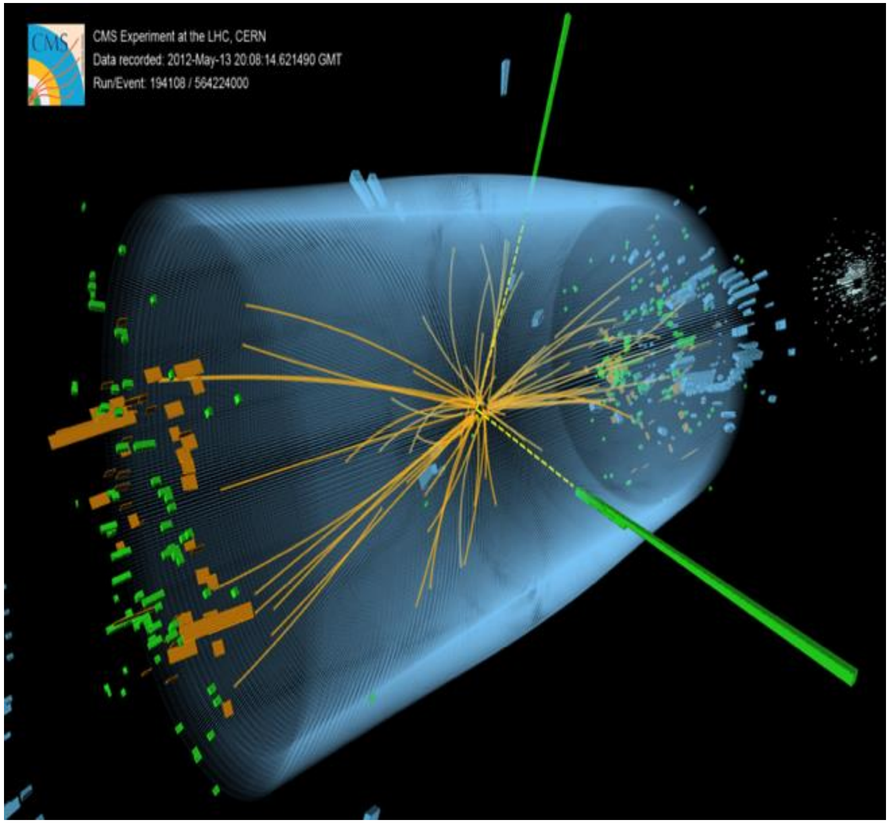


November 2010
Ions



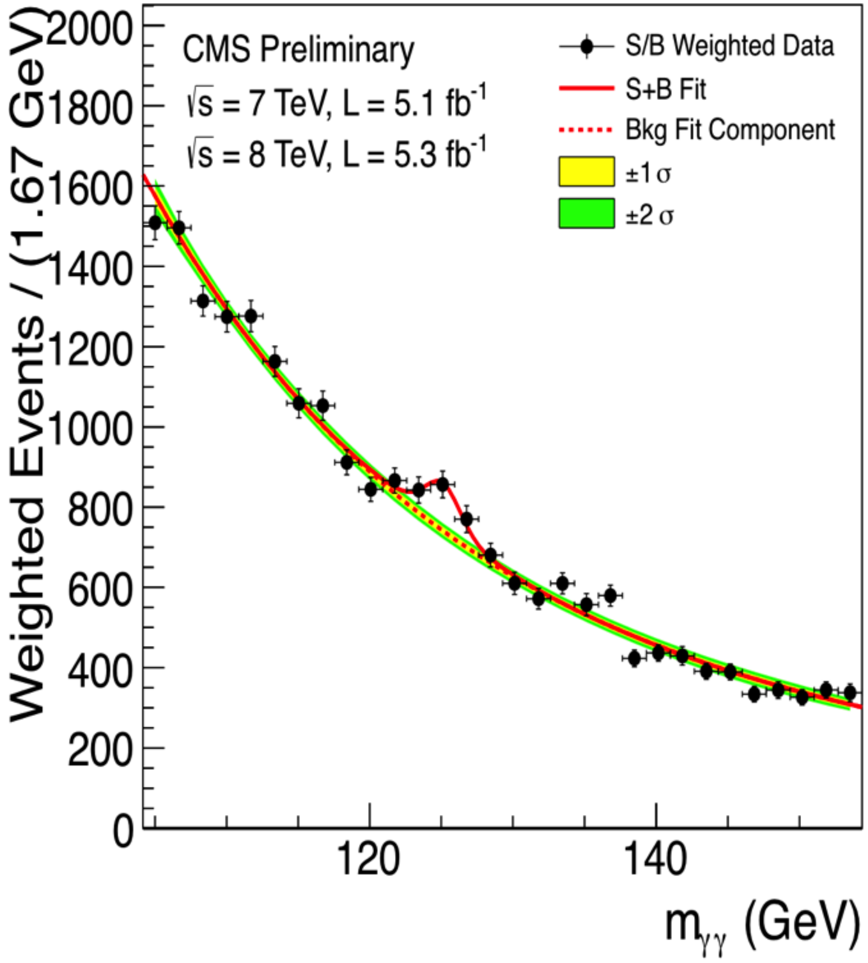
18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

pp → H → γγ



Dots = Datos

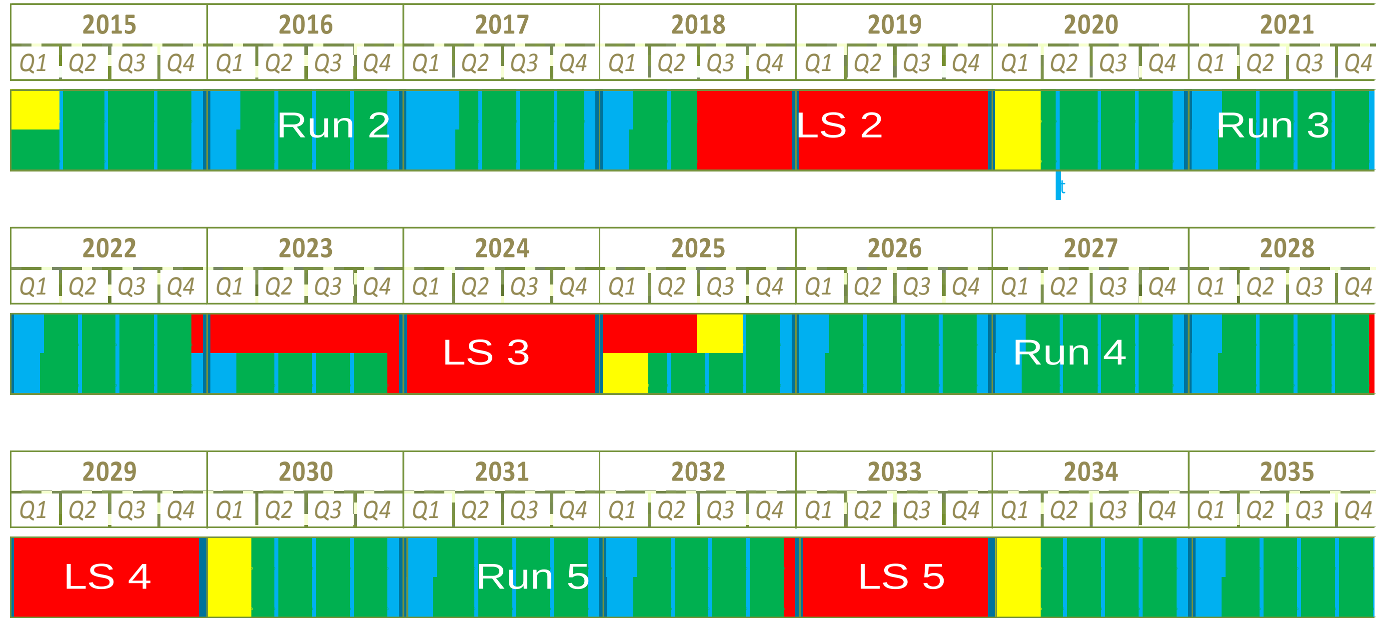
Lines = Simulation



• Future•

CERN’s priority is the explotation of the LHC to its maximum potential… 2035

- 2008 – 2012 7-8 TeV ~ 2000 Higgs
- 2015 – 2018 13-14 TeV



• Ex. Detector Upgrade LS1•

ATLAS Tracker (Pixel System Upgrade)

Motivation:

- Pattern recognition robustness for higher track multiplicity
- Controlling detector occupancy at high luminosity
- Tracking precision for excellent vertex detector performance

Actions

- Removed Pixel detector to surface
- Redone all services, doubling readout speed for Layer 2
- Repair non-working modules, recovered from 95% to 98%
- New, smaller beam pipe
- Added new innermost sensing layer (IBL), using most advanced technology for sensors, electronics, and thermal management
- Installed a new array of telescopes for beam monitoring

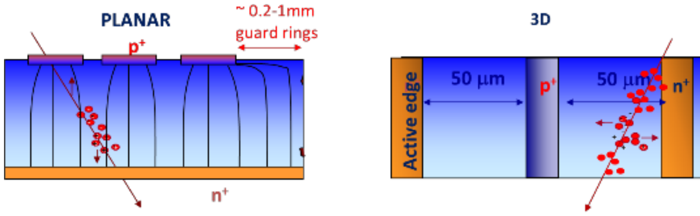
Further Detector Upgrades

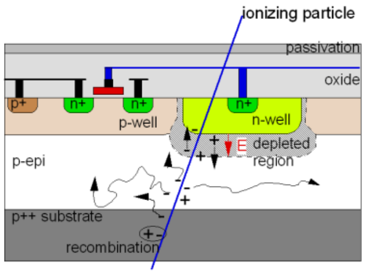
The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier

- Must replace inoperable detector elements (rad damage)
- Must upgrade electronics to cope with increased rates

Trackers R&D Efforts

- Improved radhard
- Optimization of sensor thickness (reduced leak current) and geometry (better overlap, less material)
- 3D sensors
- Combine sensor and electronics in one chip (MAPS on CMOS)
- On detector thermal management (CO_2)
- …
- Scintillating Fiber Tracker (LHCb)

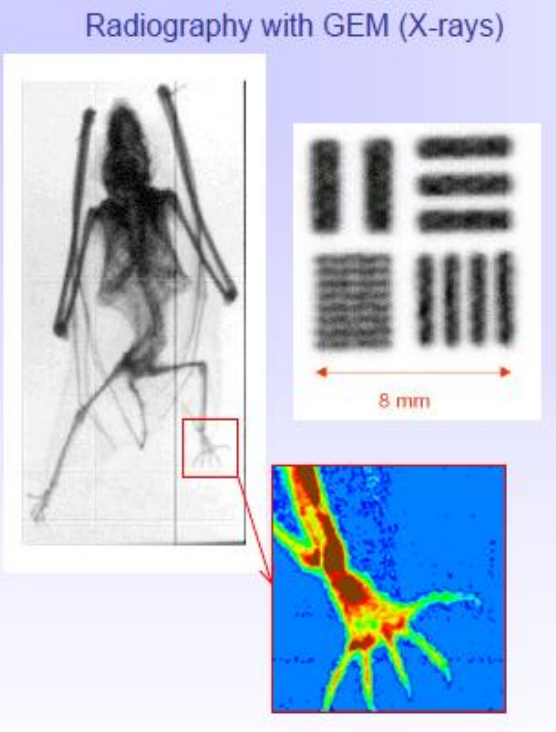




• Detector Upgrades•

- **Calorimeters R&D Efforts**, towards rad tolerant systems
  - Rad-tolerant crystal scintillators (LYSO, YSO, Cerium Fluoride), WLS fibres in quartz capillaries, rad-tolerant photo-detectors (e.g. GaInP), change layout of tile calorimeter using WLS fibres within scintillator to shorten the light path length, High granularity Particle flow / Imaging Gas Calorimetry (CALICE)…
  - *Electronics upgrades:* On-detector front-end electronics with sufficient resolution and large dynamic range
- **Muon systems R&D Efforts**
  - Improved rate capability and timing, using novel detector technologies (e.g. MPGD)
- **Electronics**
  - Development of new front-end chips to cope with increased channel densities, develop high density interconnects, optiize power distribution, develop High speed links (≳10 Gbps)
- **Trigger/DAQ/Offline computing**
  - New trigger strategies, processing, networks, storage, CPU, CLOUD-computing…

Other Fields of Application



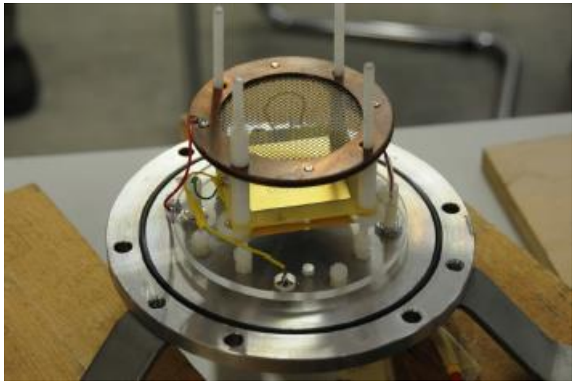
Fast and Therma Neutron Detection
Non-destructive diagnotic, Biology, Nuclear plants, …

Xray Low Energy
Radioactive waste…

Pixelated GEMs
Microdosimetry, Direct measurements with real tissue, Radon monitors….

Gamma High Fluxes
Radiotherapy…

High Intensity Beam Monitors
Hadrontherapy, Ions beam monitoring…

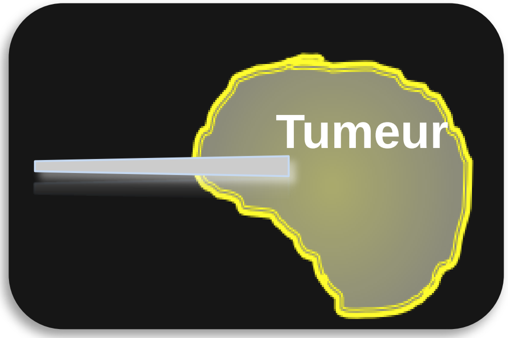


Highly sensitive GEM-based UV flame and smoke detector

RETGEM-based detectors are able to reliably detect a 1.5 m^3 fire at a ~1 km distance

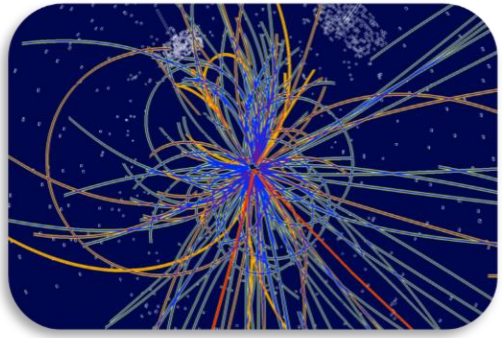
Ref. http://arxiv.org/pdf/0909.2480.pdf

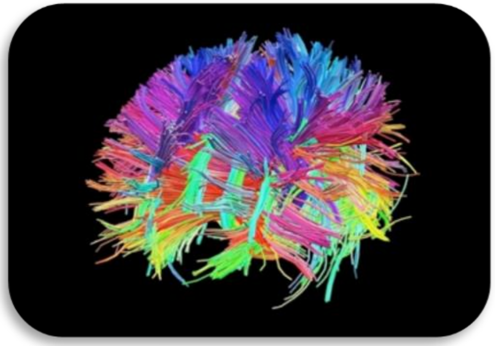
Particle
Accelerators



Radiotherapy

Particle
detection,
Track
Reconstriction





Imaging

Large Scale
Computing

Analysis,
Simulations

mar.capeans@cern.ch

Thanks for your attention!

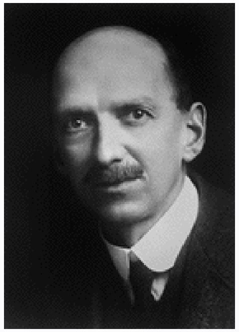
+

- *The Particle Detector BriefBook* http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- CERN summer student lectures by W.Riegler: http://indico.cern.ch/conferenceDisplay.py?confId=134370
- ICFA Schools on Instrumentation
    - The last one: http://fisindico.uniandes.edu.co/indico/conferenceTimeTable.py?confId=61#20131125

- **BOOKS:**
- K. Kleinknecht - Detectors for Particle Radiation, C.U.P. 1990
- R.K. Bock & A. Vasilescu - The Particle Detector BriefBook, Springer 1998
- R. Fernow - Introduction to Experimental Particle Physics, C.U.P. 1986
- **W.R. Leo - Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag 1987**
- G.F. Knoll - Radiation Detection and Measurement, Wiley 1989

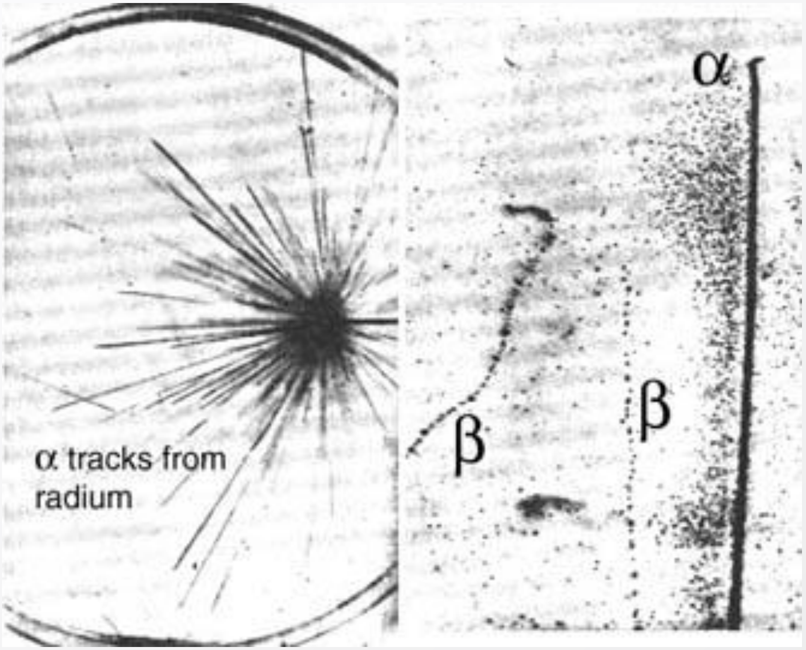
- **CERN Notes:**
- Fabjan & Fischer - Particle Detectors CERN-EP 80-27, Rep. Prog. Phys. **43** (1980) 1003
- F. Sauli - Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09

Spare Slides



C. T. R. Wilson

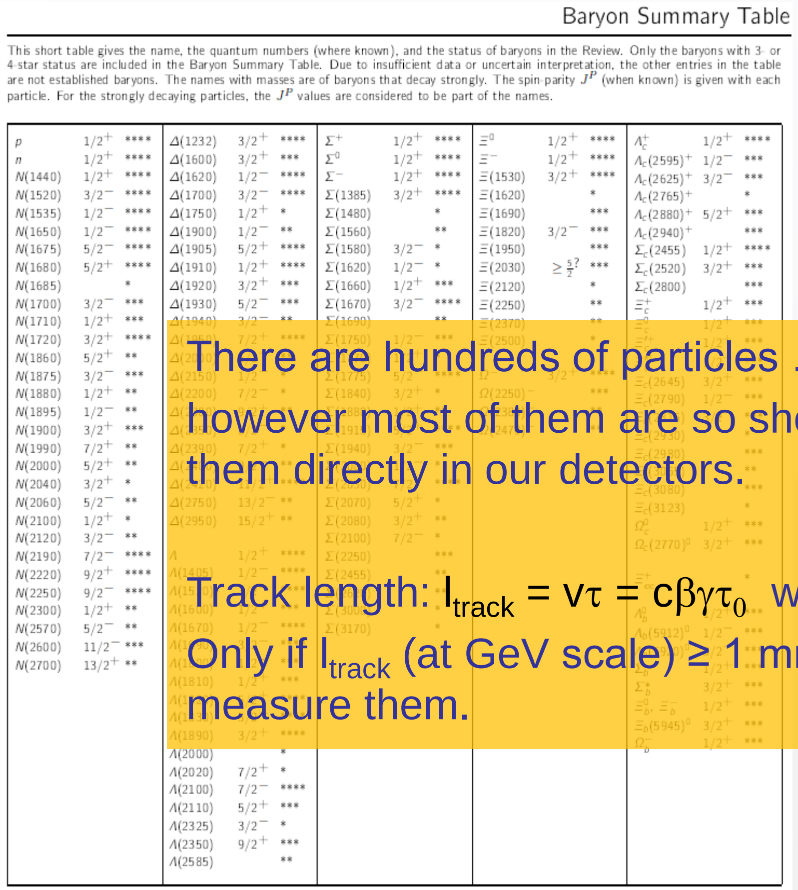
1912, Cloud chamber



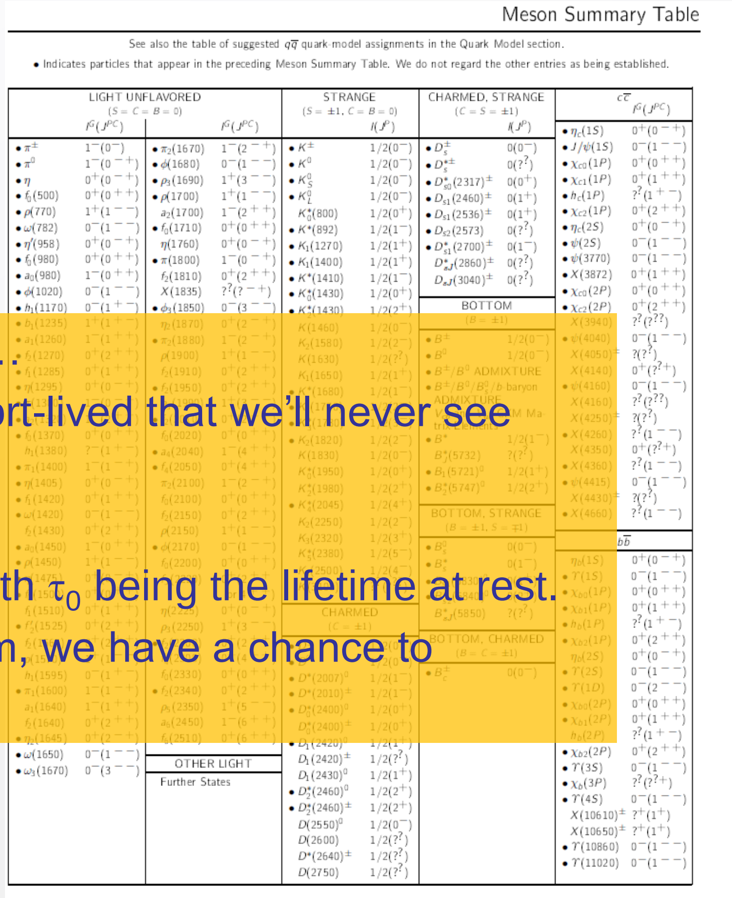
First tracking detector

The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a super-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path.

Introduction


Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.


Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

There are hundreds of particles …

however most of them are so short-lived that we'll never see them directly in our detectors.

Track length: $l_{track} = v\tau = c\beta\gamma\tau_0$ with τ_0 being the lifetime at rest.

Only if l_{track} (at GeV scale) ≥ 1 mm, we have a chance to measure them.

Leptons

- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

Gauge bosons

- γ
- $W^{+/-}$
- Z
- g
- H

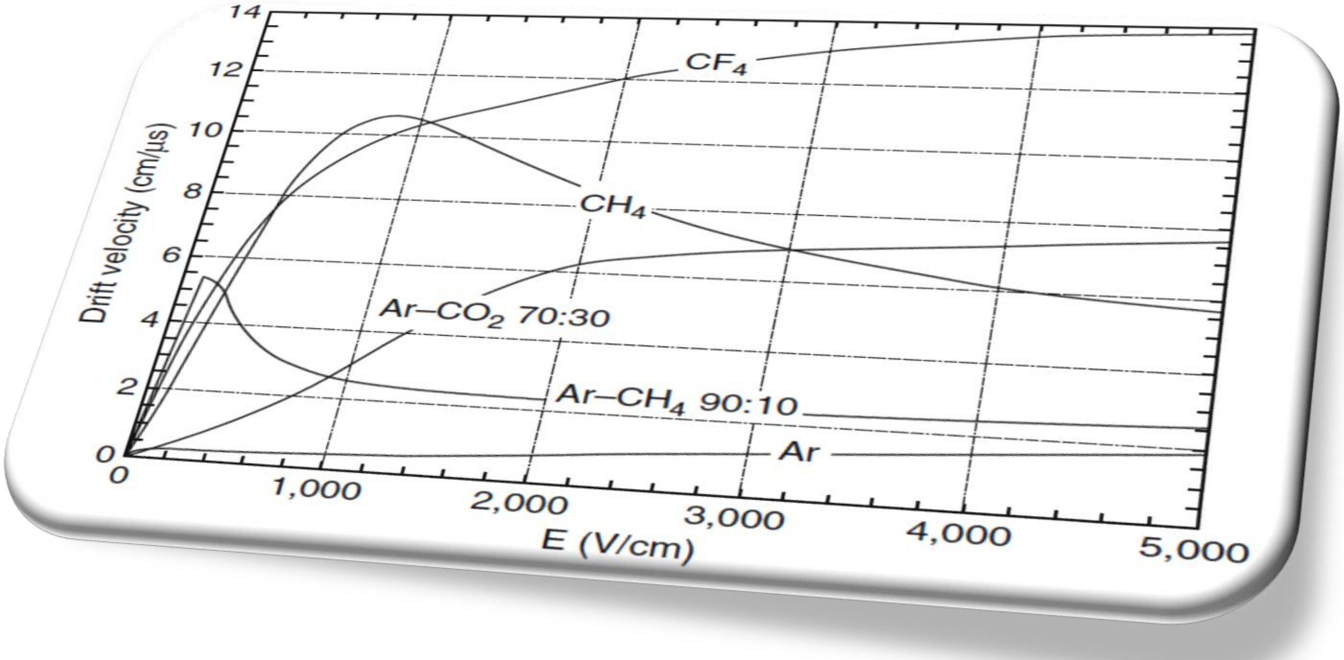
Which are left then? These 8 particles (and their antiparticles).

	γ	**p**	**n**	**e±**	$\mu^\pm$	$\pi^\pm$	**K±**	**K_0** (K_S/K_L)
τ_0	∞	∞	∞	∞	2.2μs	26 ns	12 ns	89 ps / 51 ns
l_{track} (p=1GeV)	∞	∞	∞	∞	6.1 km	5.5 m	6.4 m	5 cm / 27.5 m

Drift and Mobility

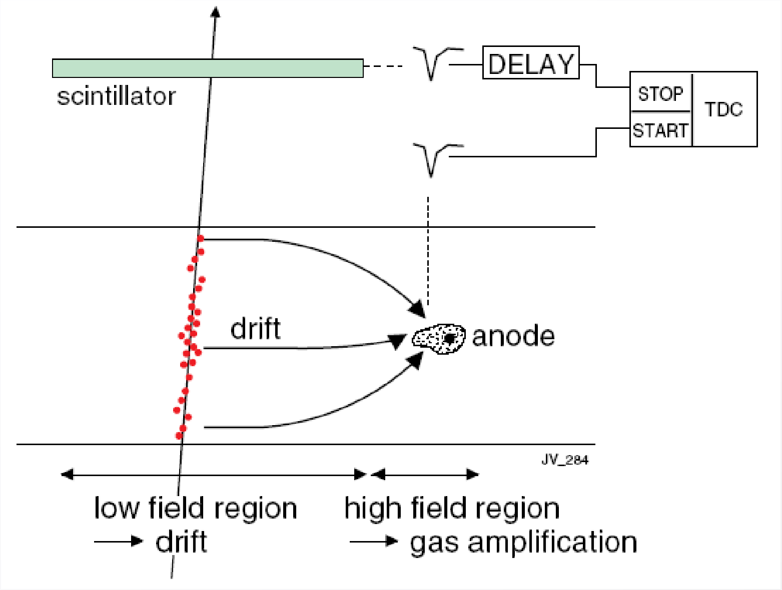
In an external E-field electrons/ions obtain velocity **v**$_D$ in addition to thermal motion; on average electrons/ions move along field lines of electric field E

- **v**$_D = \mu_\pm |E|$
- Ions move at cm/ms while electrons move at cm/μs
- Collection time is inversely proportional to **v**$_D$



Drift Chambers

Spatial information obtained by measuring time of drift of electrons

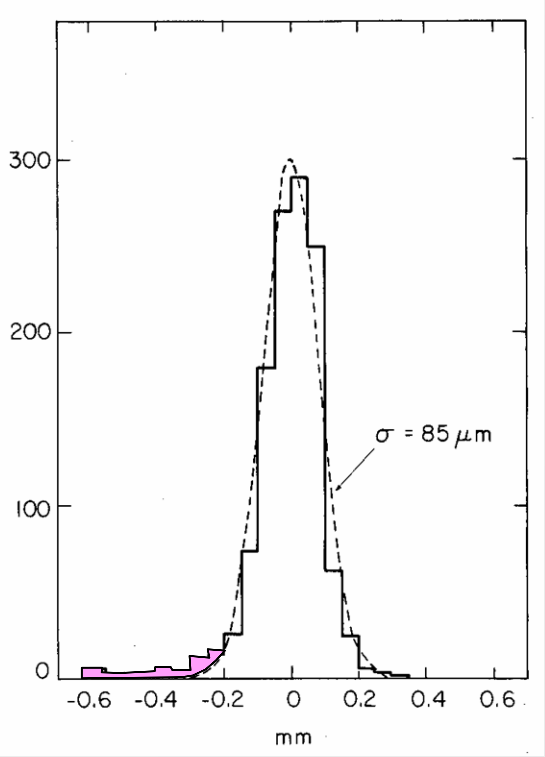


Measure arrival time of electrons at sense wire relative to a time t_0.

Need a trigger (bunch crossing or scintillator).

Drift velocity independent from E.

F. Sauli, NIM 156(1978)147

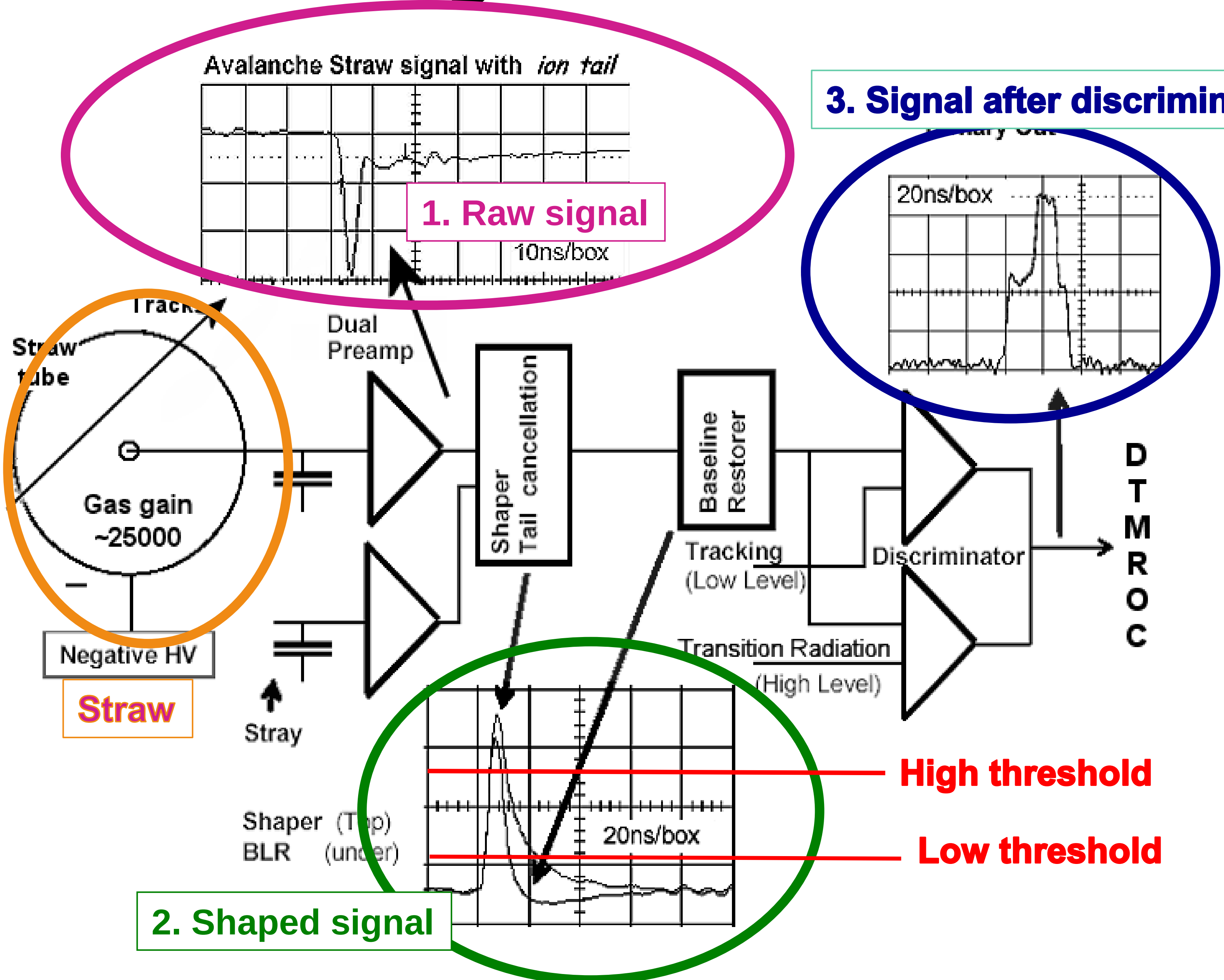


Advantages: smaller number of wires → less electronics channels.

Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics.

XII ICFA School on Instrumentation in Elementary Particle Physics, Bogota, 2013

The signal from the straw



1. Raw signal

3. Signal after discriminator

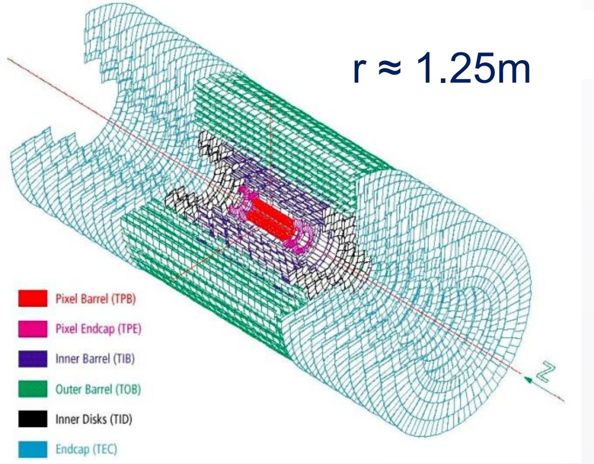
Straw

2. Shaped signal

High threshold

Low threshold

A more realistic example: CMS Silicon Tracker



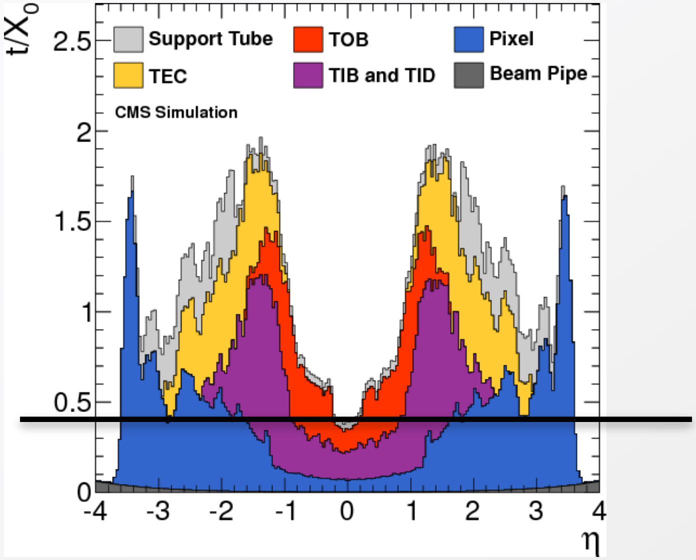
- B=3.8T, L=1.25m, average N ≈ 10 layers,
  - Average resolution per layer ≈ 25μm,

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

→ σ_p/p = 0.1 % momentum resolution (at 1 GeV)

→ σ_p/p = 10 % momentum resolution (at 1 TeV)

Material budget (Si, cables, cooling pipes, support structure…)



- B=3.8T, L=1.25m, $t/X_0 \approx$ 0.4-0.5 @ $\eta < 1$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\frac{1}{B\sqrt{LX_0}} = 0.045\frac{1}{B\cdot L}\sqrt{\frac{t}{X_0}}$$

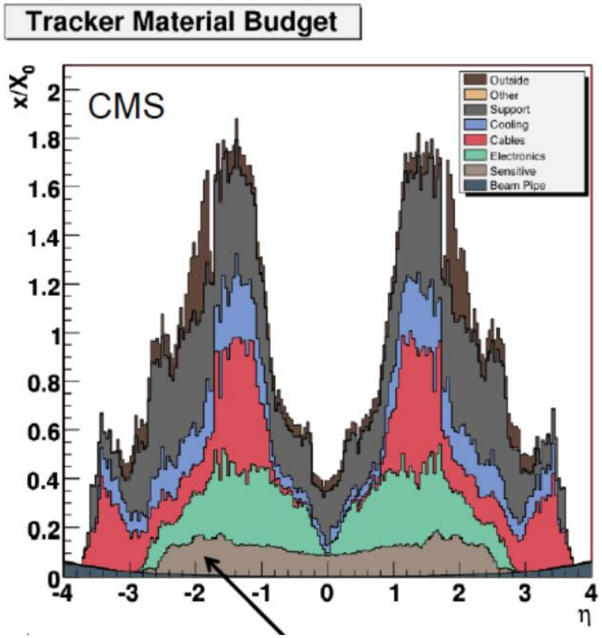
→ σ_p/p = 0.7% from multiple scattering

(η = pseudo rapidity: $\eta = -\ln(\tan\frac{\theta}{2})$)

Precision Trackers

Slide: P.Wells, CERN

- Intrinsic space point resolution
  - Sensor design (pixels, strips, gas detectors…)
- Magnetic field
  - Strength, and precise knowledge of value
- Alignment
  - Assembly precision, survey, stability
  - Measure the positions of detector elements with the tracks themselves
  - Control systematic effects
- Multiple scattering and other interactions
  - Minimise the material
  - Measure the amount of material in order to simulate the detector and reconstruct tracks correctly
  - Also affects energy measurement in calorimeter

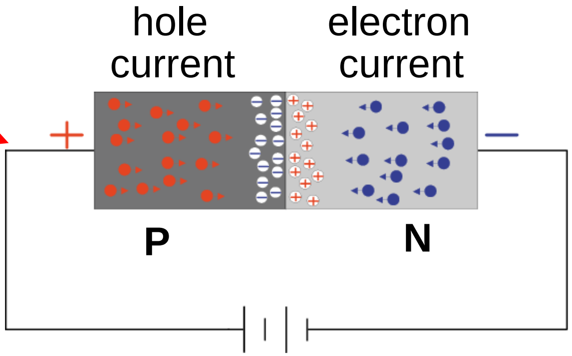


The basics of a silicon detector: p-n diode

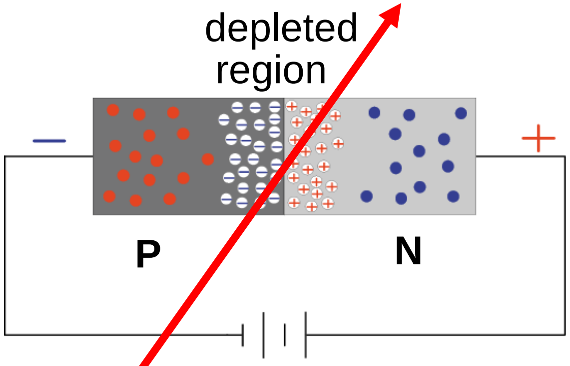
- Basic element of a solid state (silicon) detector is... a diode
  - p-type and n-type doped silicon material is put together

more holes **more electrons**

Current flow through diode if connects like this



  - for particle detectors: reverse bias the diode to create an active detection layer



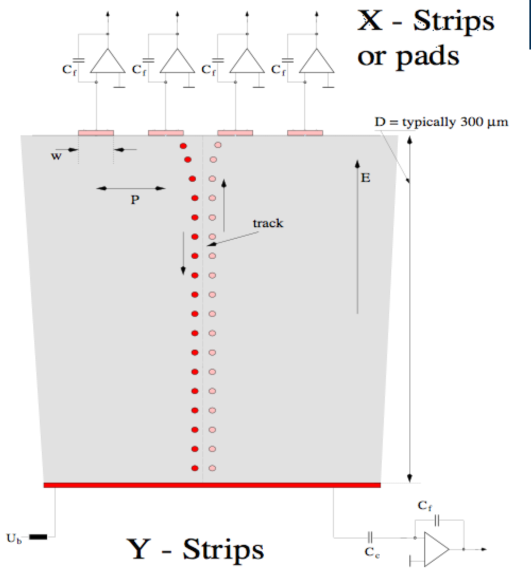
- **Depletion layer : zone free of mobile charge carriers**
  - **no free holes, no electrons so that we can observe the ionization charge**
  - **thickness of depletion region depends on voltage, doping concentration**

charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

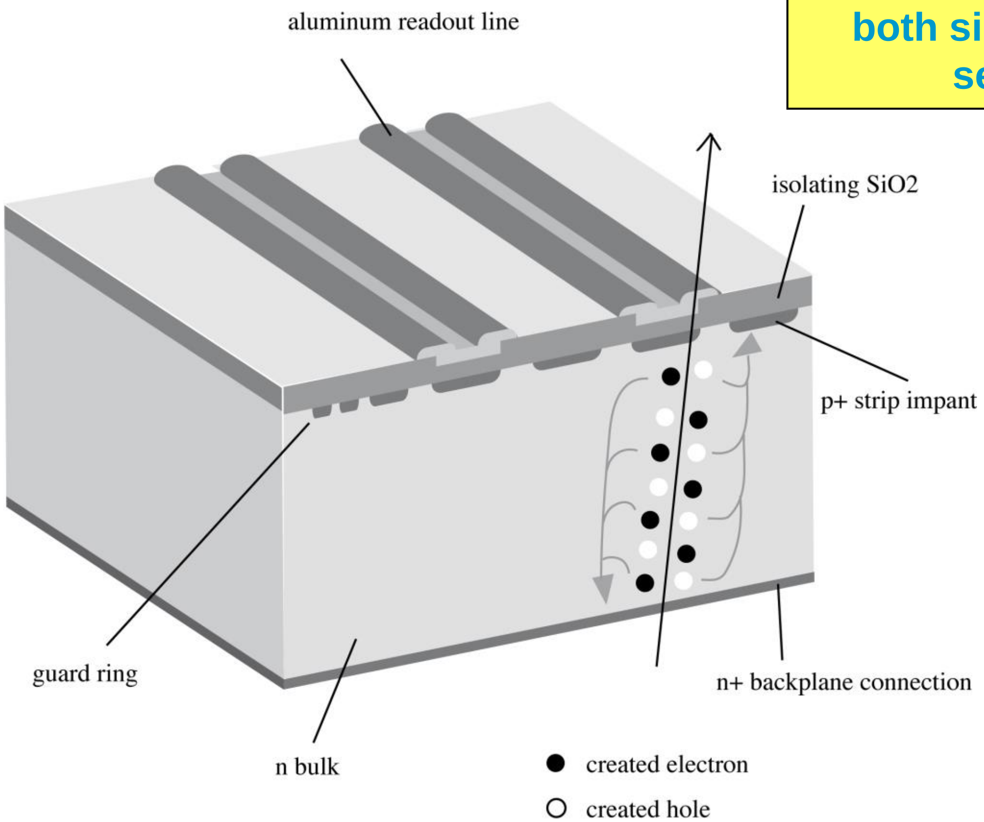
typically 20000 - 30'000 electron/hole pairs in 300 µm thick material
Compare to intrinsic Si: $4.5 \cdot 10^8$ per detector/cm^2

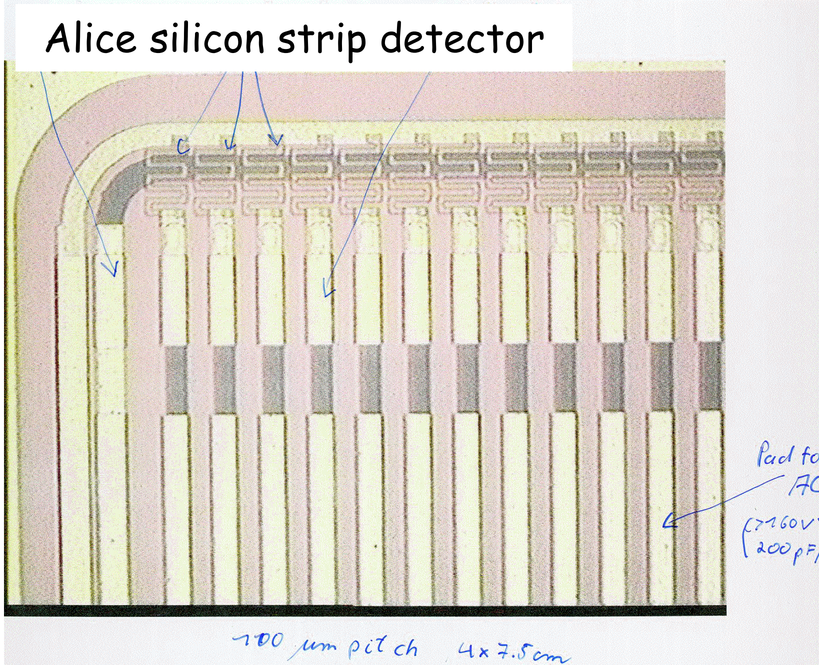
… and now segment the wafer

- Many diodes on the same wafer
  - Big advantage of planar fabrication process: can integrate many channels in very small space (typical dimensions for particle detectors: 25 to 50μm channel spacing)



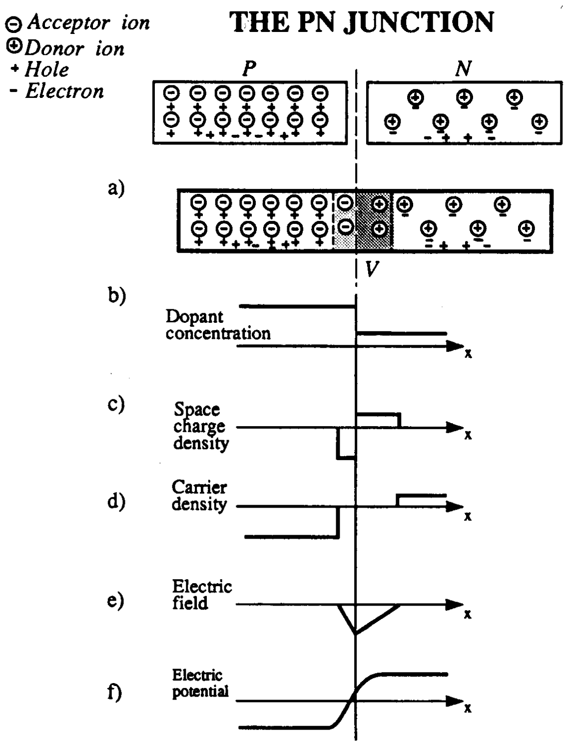
Can also do strips on both sides to get 2-D sensitivity




Alice silicon strip detector

100 μm pitch 4x7.5cm

Operation



- electrode (p+)
  - Want shallow electrode → high doping concentration ~10^{15} cm^{-3} (p$^+$)
- Want deep bulk (n) as detector
  - Lower doping concentration ~10^{12} cm^{-3}
- Apply reverse bias voltage
  - Creates depletion layer
  - Acts as drift field for ionization charge

Full depletion voltage (voltage at which the depletion reaches the ohmic side)

$$\rho = \frac{1}{q \mu_e N_d}$$

$$V_{fd} = \frac{T^2}{2\varepsilon\rho\mu}$$

Want high resistivity material (~5kOcm) for practical operation voltage (50 to 100V)

- Band gap: E_g =1.12 V.
- E(e$^-$-hole pair) = 3.6 eV, (≈ 30 eV for gas).
- High specific density (2.33 g/cm^3) → large ΔE/track length for M.I.P.'s.: 390 eV/μm ≈ 108 e-h/ μm (average)
- High mobility: μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs
- Thickness ~0.3mm

Basics of photon detection

Requirements on photodetectors

- High sensitivity, usually expressed as: quantum efficiency $QE(\%) = \frac{N_{pe}}{N_{\gamma}}$

  or radiant sensitivity S (mA/W), with $QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)}$

QE can be >100% (for high energetic photons) !

- Good Linearity: Output signal ~ light intensity, over a large dynamic range (critical e.g. in calorimetry (energy measurement).
- Fast Time response: Signal is produced instantaneously (within ns), low jitter (<ns), no afterpulses
- Low intrinsic noise. A noise-free detector doesn't exist. Thermally created photoelectrons represent the lower limit for the noise rate ~ $A_o T^2 \exp(-eW_{ph}/kT)$. In many detector types, noise is dominated by other sources.
- + many more (size, fill factor, radiation hardness, cost, tolerance/immunity to B-fields…)

Energy resolution

- Number of particles in shower should be proportional to energy of initial particle $N_{track} = \frac{E}{E_c}$
  - error of energy measurement mainly determined by fluctuations in the number of tracks $s(N_{track}) = \sqrt{N_{track}}$
  - so the relative energy measurement error is $\boxed{\frac{s(E)}{E} \mu \frac{1}{\sqrt{E}}}$
- This is just the statistical (stochastic) measurement error
  - more contributions come fron r inhomogenities and noise
  - in general

convolution

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}}$$

this relationship is valid both for homogeneous + sampling calorimeters and for both electromagnetic and hadronic calorimeters

stochastic term

number of shower particles

constant term

inhomogenities
non-linearities

noise term

electronics noise

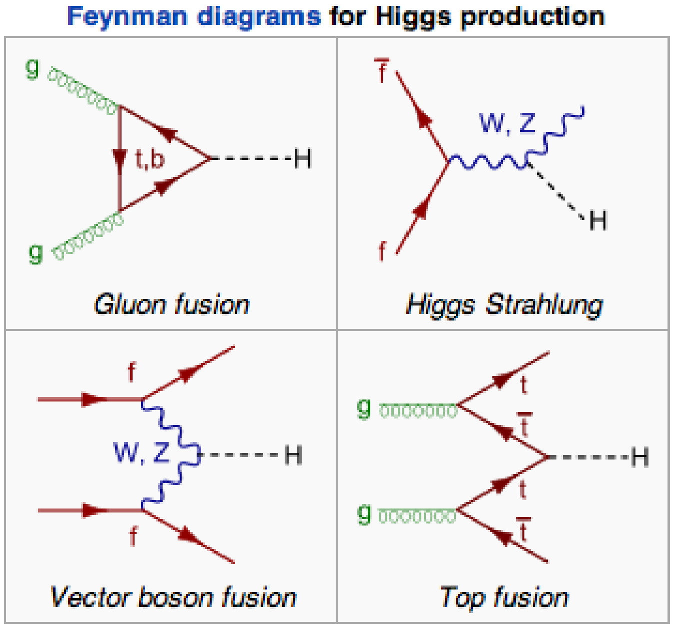
Calorímetro electromagnético (e$^-$, γ)

[redacted]

Calorímetro hadrónico (n,p,mesones)

Detección del Higgs

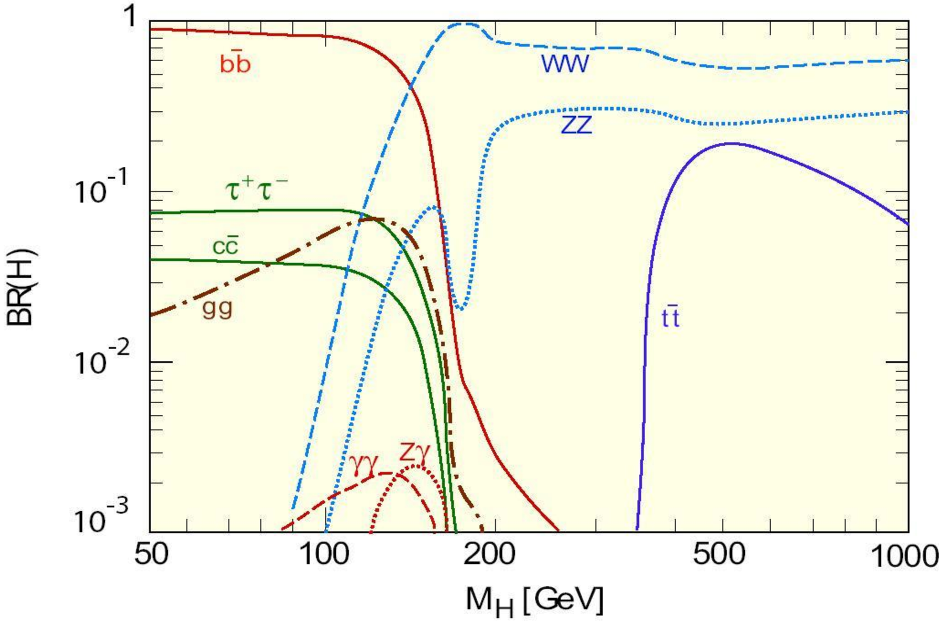
Producción del Higgs



~ 1 Higgs / 10^9 LHC collisions

Se desintegra inmediatamente en partículas mas ligeras

- H→2 fotones (H→γγ)
- H→ 4leptons, 4muons, 4e, 2muons+2e



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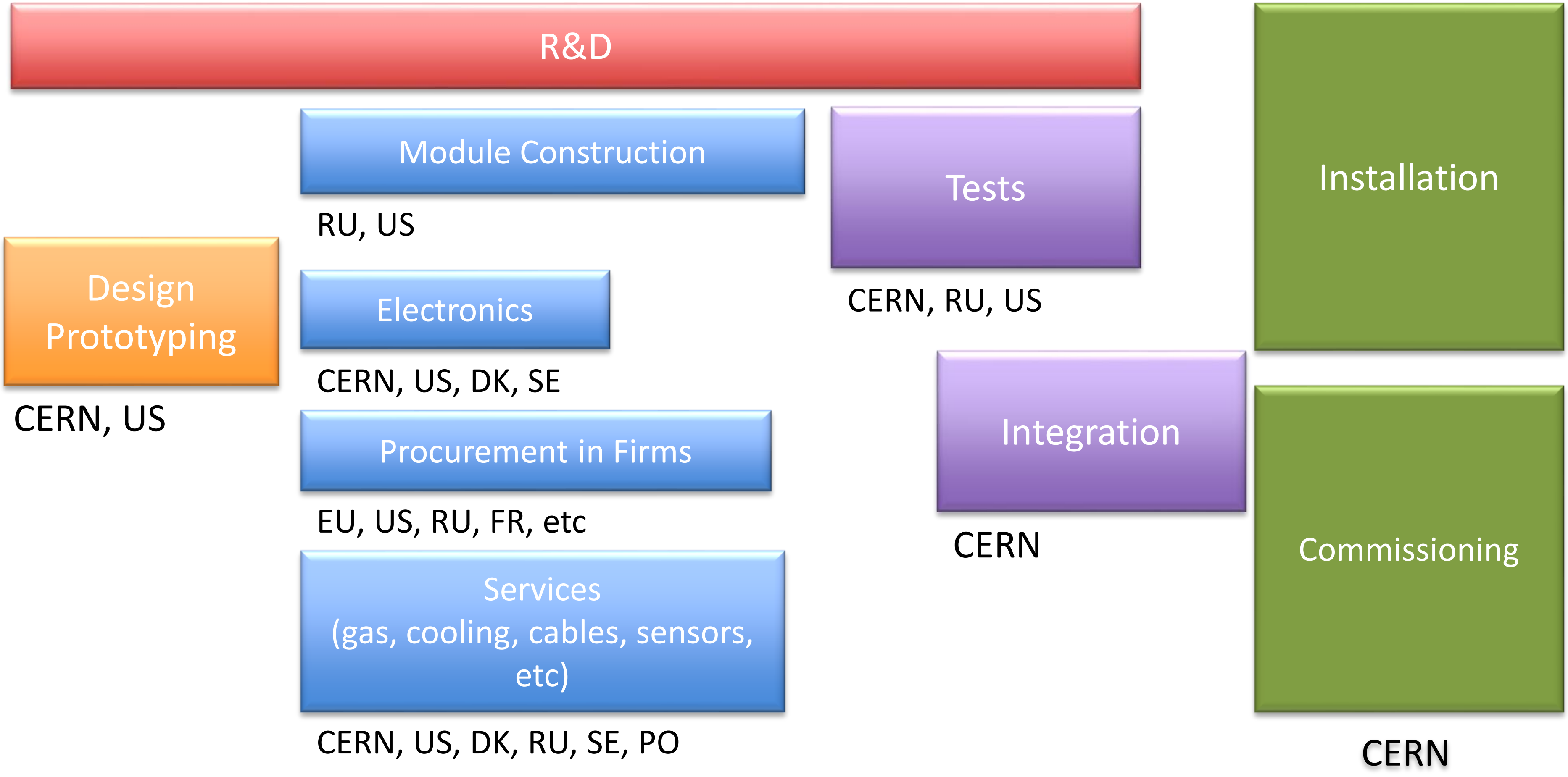
Distributed/Collaborative Projects

Example, the ATLAS Transition Radiation Tracker *(non-exhaustive list!)*



R&D

Design Prototyping

CERN, US

Module Construction

RU, US

Electronics

CERN, US, DK, SE

Procurement in Firms

EU, US, RU, FR, etc

Services (gas, cooling, cables, sensors, etc)

CERN, US, DK, RU, SE, PO

Tests

CERN, RU, US

Integration

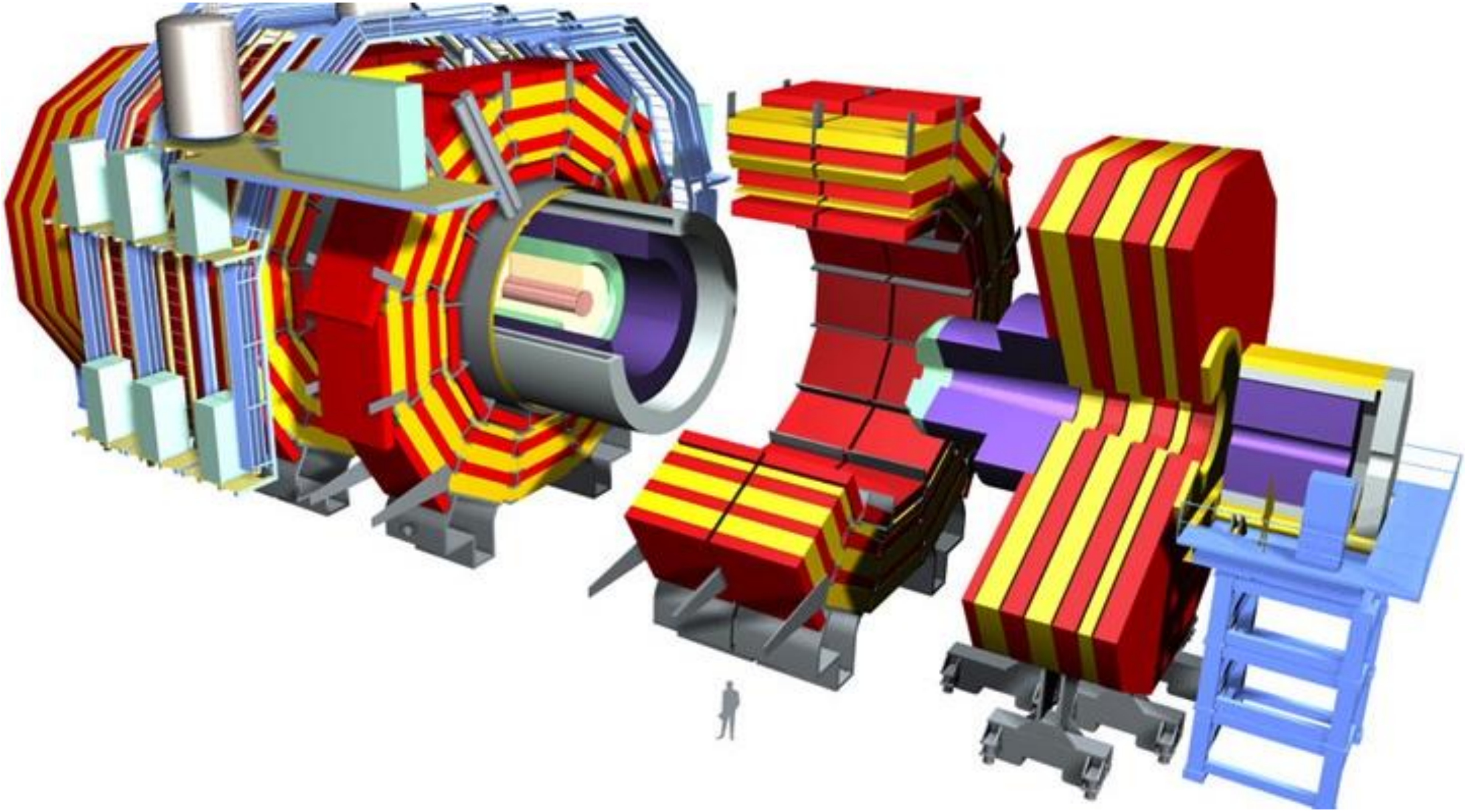
CERN

Installation

Commissioning

CERN

Detector CMS



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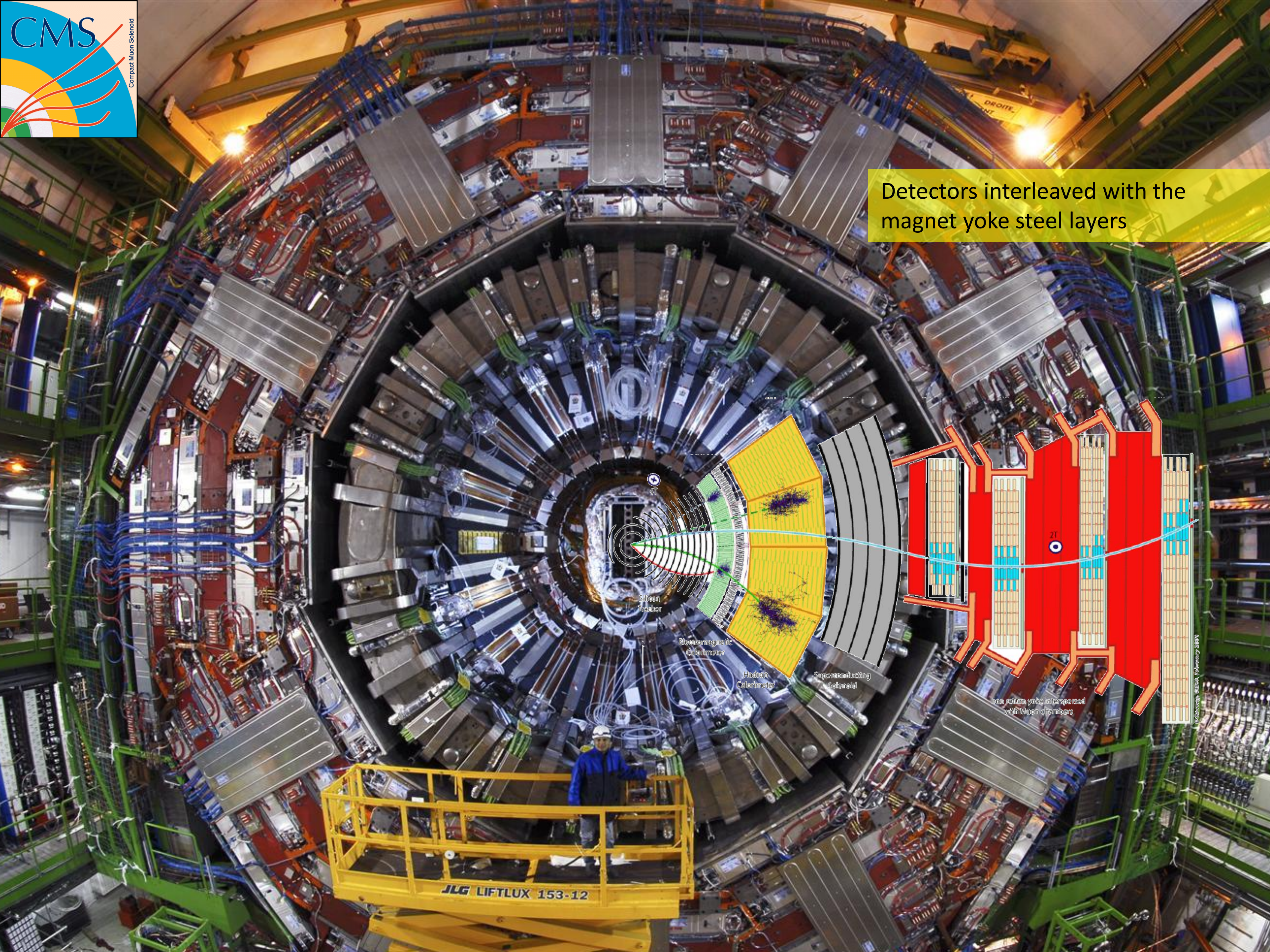
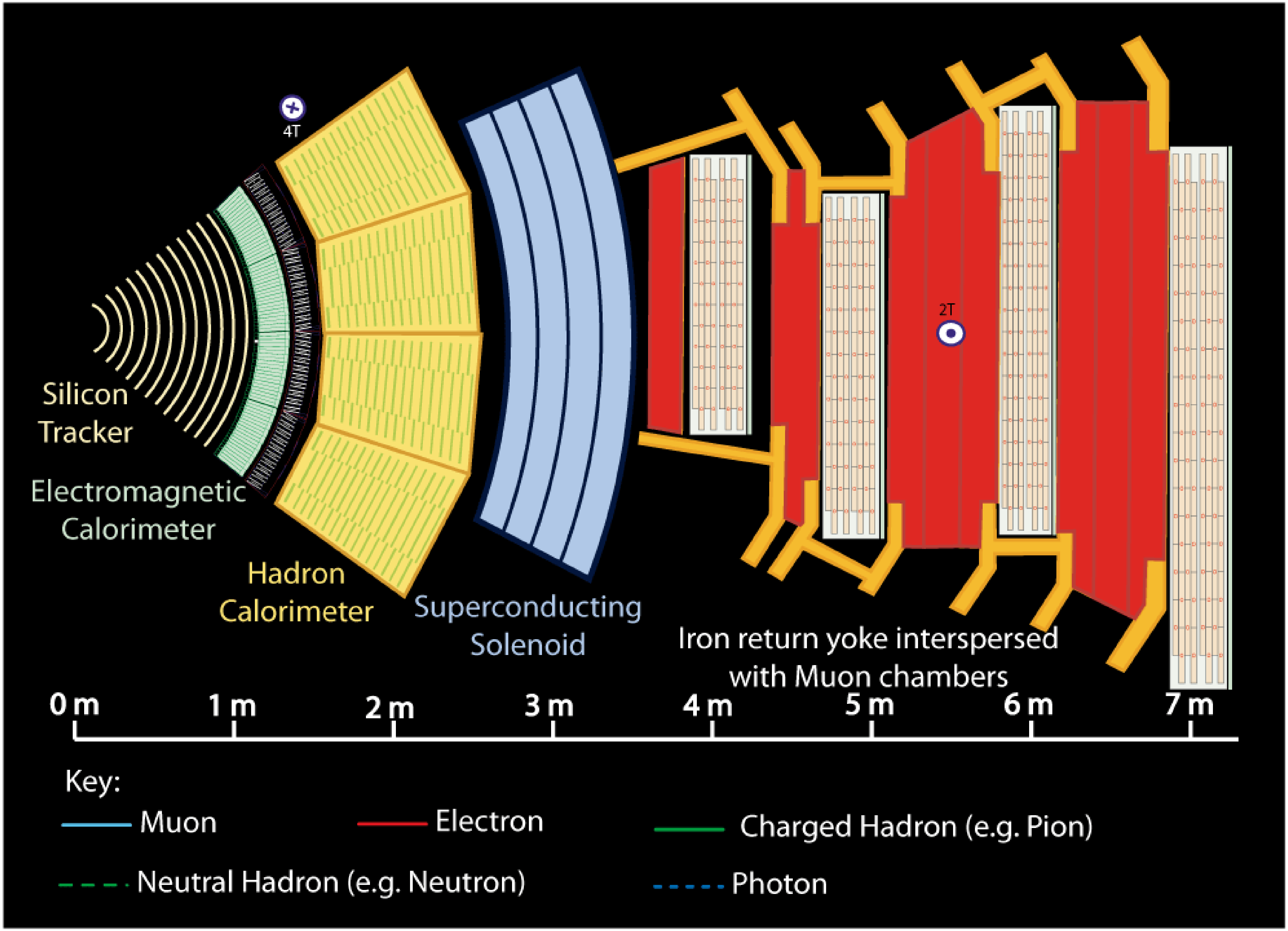
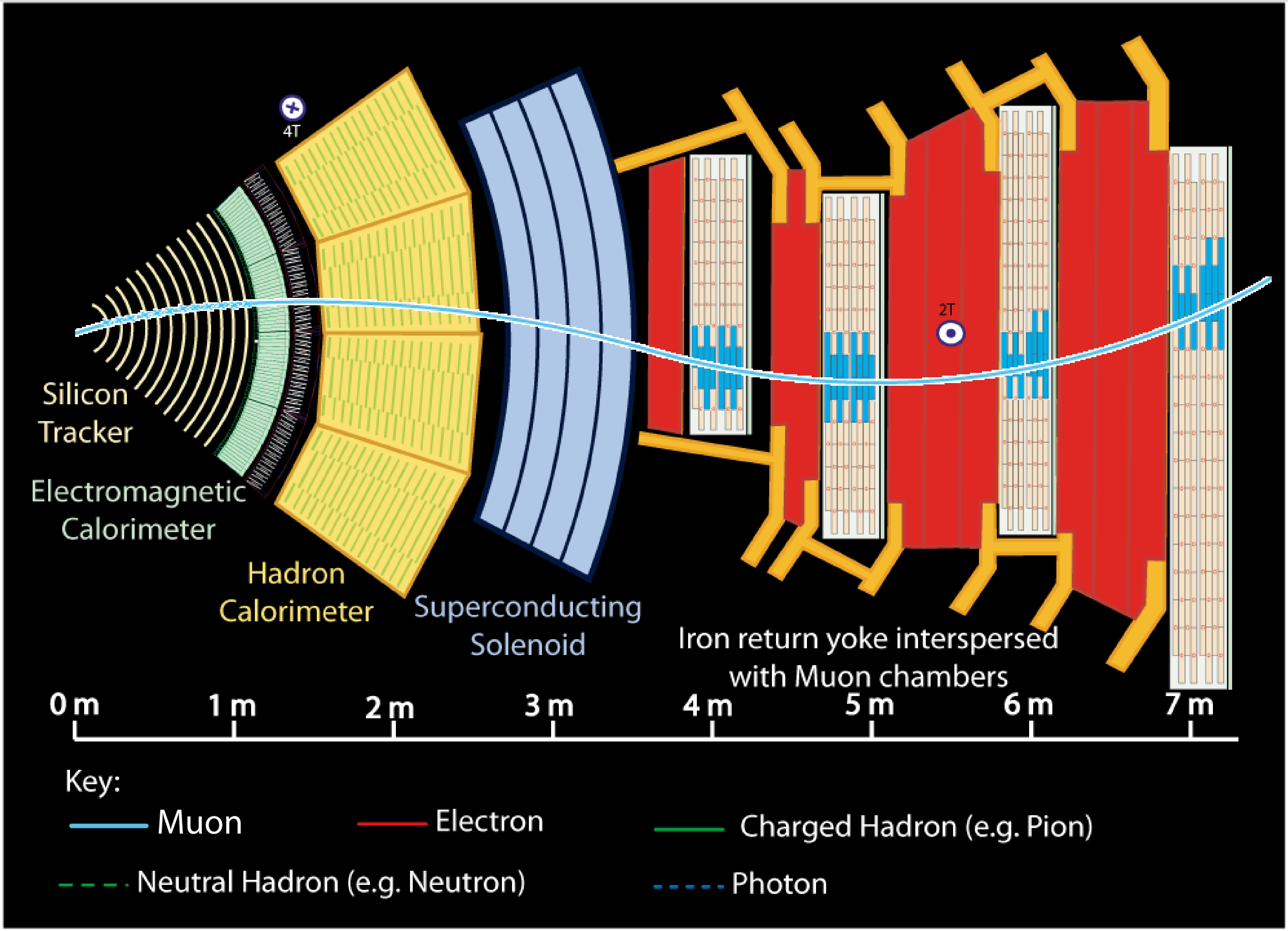
Detectors interleaved with the magnet yoke steel layers




4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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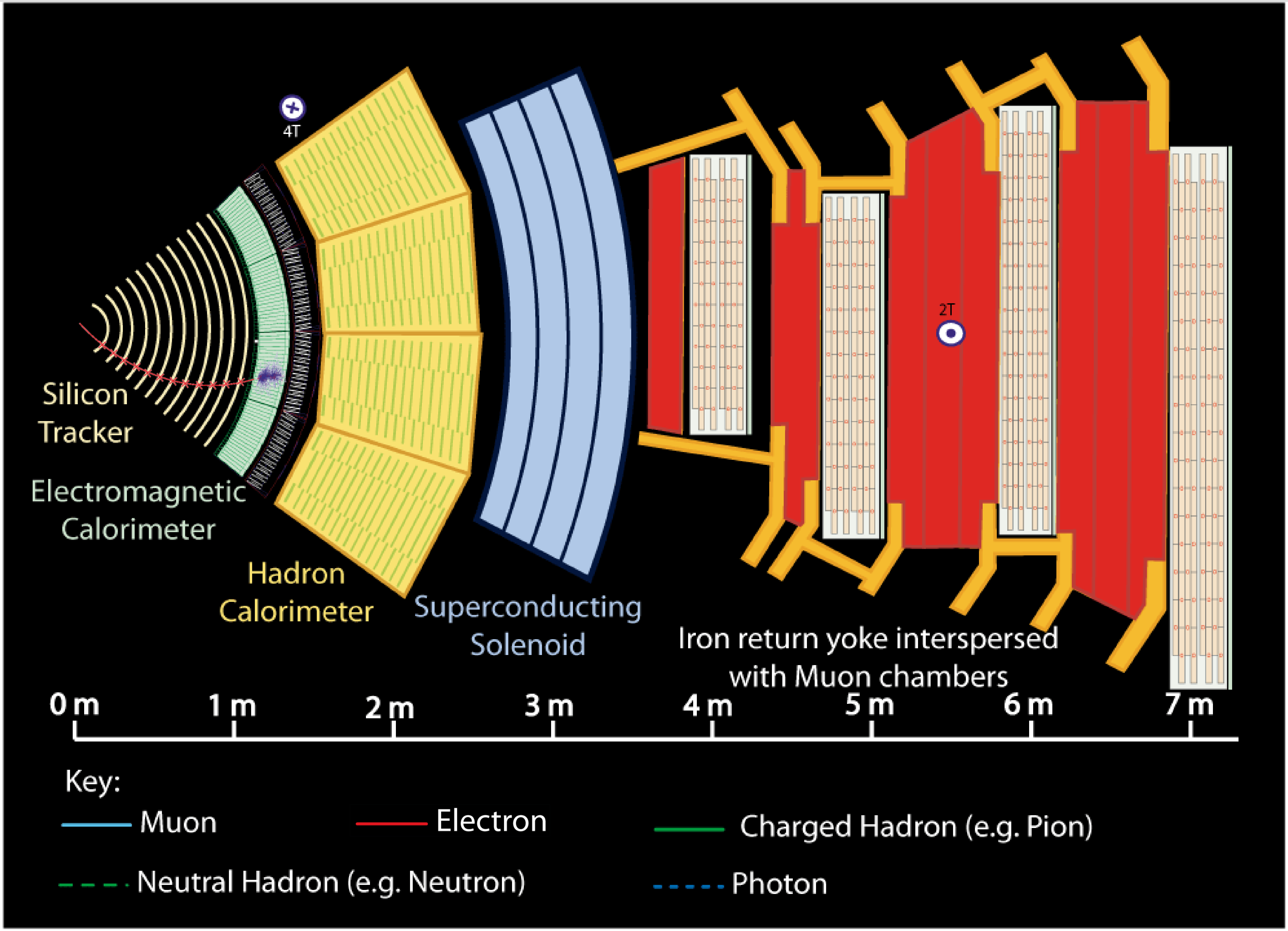
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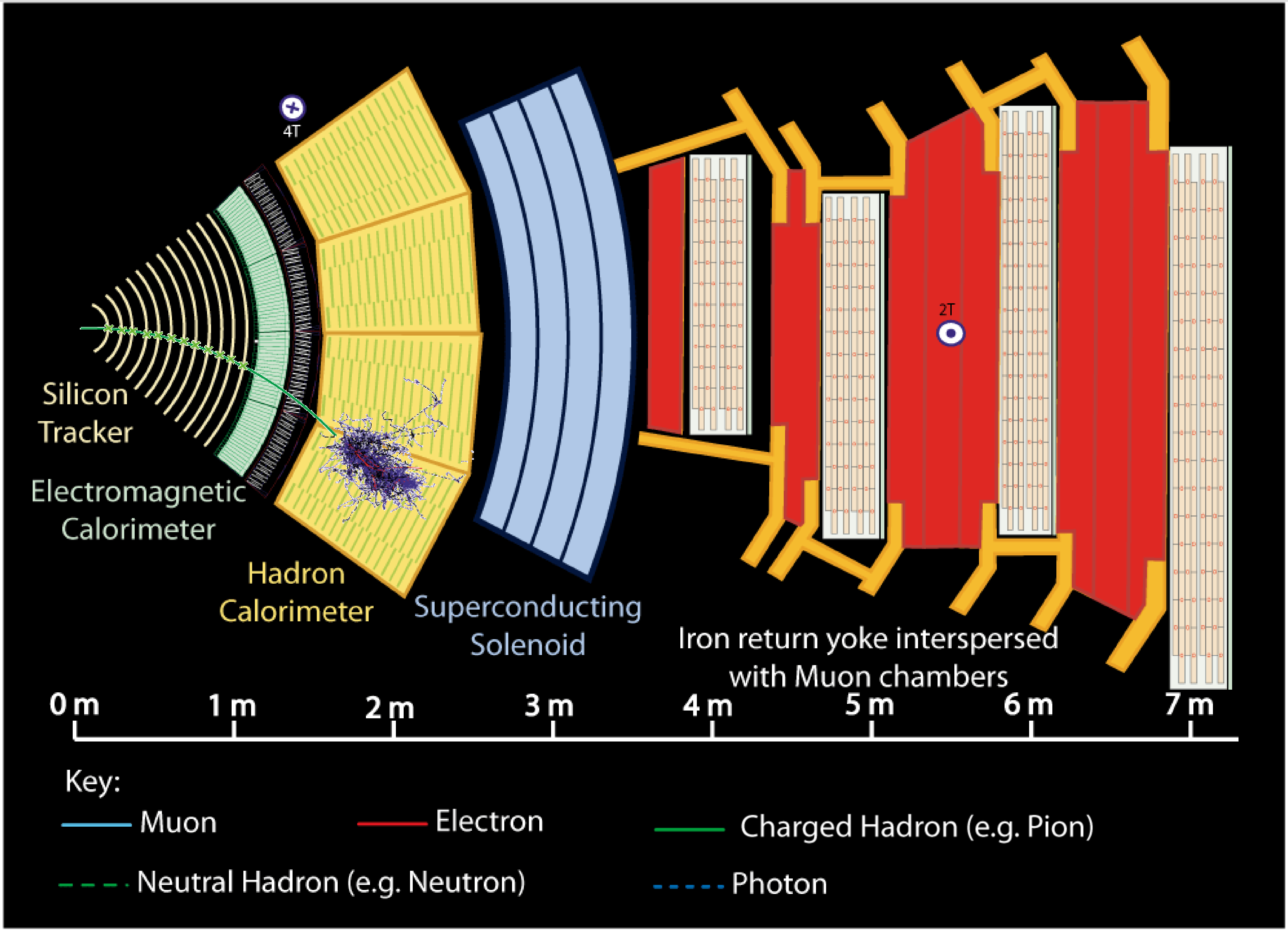
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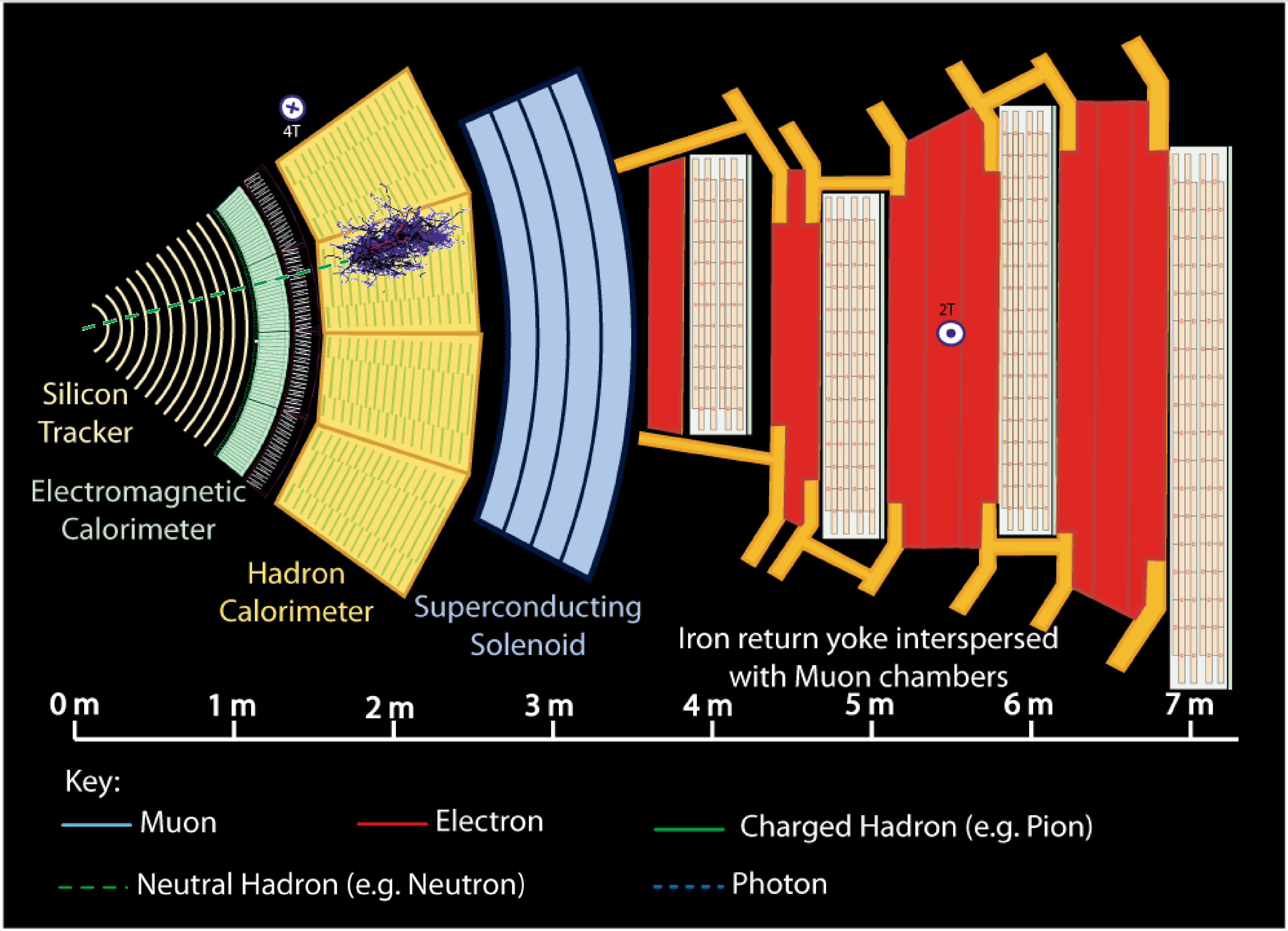
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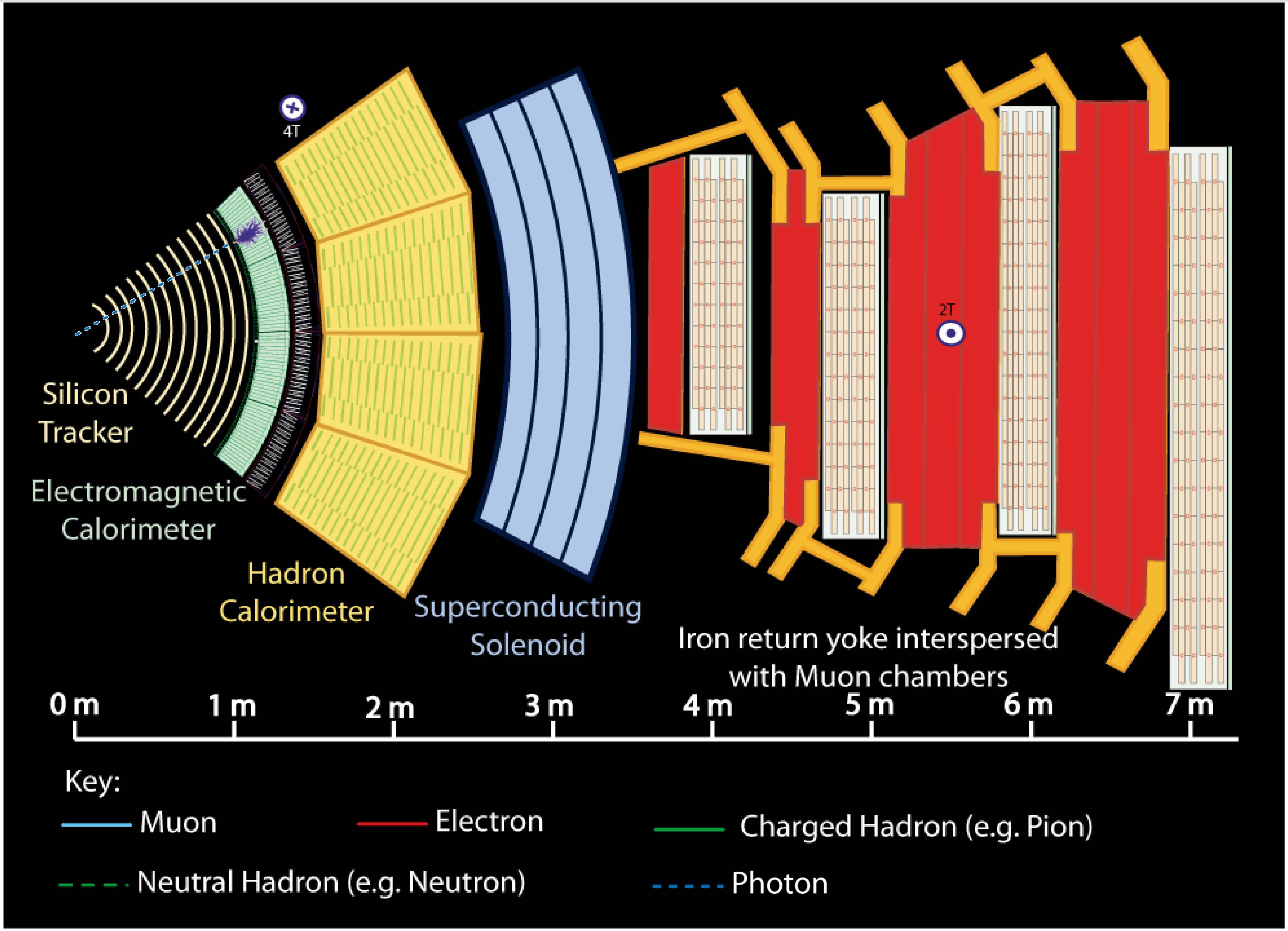
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